A Cross-System Instrumental Voice Profile of the Aging Voice:

With Considerations of Jaw Posture Effects

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ABSTRACT

Purpose: An open mouth approach is used in voice therapy for enhancing speech and voice production and relaxing the laryngeal musculature. The acoustic and physiological consequences of an open jaw posture, however, have not been clearly understood due to a paucity of cross-system studies taking the age effect into consideration. The major aims of this study are twofold (1) to examine if the geriatric voice may be improved using an "open jaw" posture and (2) if an aging effect on the voice of normal healthy adults can be detected through acoustic and physiological measures

Method: The main part of this study involved simultaneous multi-channel voice recordings obtained from 85 healthy adults aged between 38 and 93 years. A convenience sampling strategy was used to recruit at least five females and five males in each of four age groups, "35-59 years" (35+), "60-69" (60+), "70-79" (70+), and "above 80" (80+). For simultaneous acoustic, electroglottographic (EGG), and jaw displacement recordings, participants were asked to perform two tasks which included a sustained vowel task and a sentence production task. The sustained vowel task involved sustaining the vowel /a/ in five different conditions, an isolated vowel /a/ produced at normal, low, and high pitch levels and the vowel /a/ initiated with a consonant (/m/ and /h/). The sentence production task involved production of the sentence "We saw two cars," containing the vowels /i, ɔ, u, a/. For simultaneous airflow-EGG recordings, participants were asked to sustain the vowel /a/ at normal pitch. For simultaneous airflow-air pressure-EGG recordings, participants were asked to repeat /pa/ five times in one breath. Participants were asked to perform all of the tasks using two jaw postures (normal and open). A series of univariate analysis of

variances were used to identify instrumental measures sensitive for discriminating between the four age groups and the two jaw postures. A follow-up perceptual study was conducted to determine the effect of an open jaw posture on vowel intelligibility and voice clarity. A quota sampling strategy was used to recruit 40 normal hearing participants, including 20 females (age range = 18-42 years, mean = 25.3, SD = 7.9) and 20 males (age range = 18-47, mean = 23.6, SD = 6.7). These listeners were presented with vowels segmented from the sentences recorded in the first experiment and asked to perform a vowel identification and a voice clarity discrimination task. The vowel samples were taken from 40 speakers, with five females and five males in each of the four age groups (35+, 60+, 70+, and 80+). The percentages of correct vowel identification for voices produced with normal and open jaw postures were compared. The percentages of vowels judged as "clearer" in a normal-open jaw contrast pairs were also calculated for comparison.

Results: Significant age group effects were found in this study for both genders on fundamental frequency (F0), voice onset time (VOT) (/ka/), open quotient (OQ), and speed quotient (SQ), with additional age differences detected for females on %jitter, %shimmer, signal-to-noise ratio (SNR), and the second formant frequency (F2), and for males a significant age group effect was found on VOT (/tu/). Results for both females and males revealed significant open jaw posture effects on F0, F2, VOT (/ka/), MFR, SPL and vowel space area. In addition, for females significant posture effects were found on F1, subglottal pressure and the H1-H2 amplitude difference, and for males, significant posture effects were found on %jitter and VOT-/tu/. Results from the follow-up perceptual study revealed that an open jaw posture was associated with better vowel identification and better voice clarity.

Conclusions: A selection of instrumental measures was shown to be useful for detecting voice changes due to aging. Instrumental and perceptual evidence was found that an open jaw posture was associated with positive changes in vocal behaviours, including improved phonatory stability, vocal power, and voice clarity.

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Chapter 1. INTRODUCTION

This study investigates signs of vocal aging and the impact of jaw posturing on voice using a cross-system instrumental approach. This chapter provides an overview of the background and the rationale for the investigation.

1.1 Background

The term “geriatric”, which may be used interchangeably with “aging” and “elderly”, is often employed by voice researchers when referring to adults over age 60 years. In a survey of the research literature that investigates the geriatric voice, the ages 60 to 65 were found to most often represent the lower age boundary that differentiated “younger” from “older” participants (Ptacek & Sander, 1966a; Enderby, 1983; Ramig & Ringel, 1983; Ringel & Chodzko-Zajko, 1987; Biever & Bless, 1989; Wallace, 1991; Hoit & Hixon, 1992; Teles-Magalhaes, Pegoraro-Krook & Pegoraro, 2000; Linville & Rens, 2001; Linville, 2002). In some other studies, the “elderly” groups were found to include participants at age 70 years or older (Linville, 1987; Morris & Brown, 1987; Brown, Morris & Michel, 1989; Linville, 1992; Sato & Hirano, 1995, 1998; Ferrand, 2002; Gorham-Rowan & Laures-Gore, 2006). Despite some variations in the use of the term “geriatric”, the aging voice generally refers to the voice of individuals in later adulthood.

Advancing age has been found to result in structural changes that involve all parts of the vocal tract (Sataloff, Rosen, Hawkshaw, & Spiegel, 1997). Vocal tract changes may consequently have a substantial impact on speech production (Hoit & Hixon, 1992). This impact is often reflected in changes to voice characteristics (Luchsinger & Arnold, 1967).

Some characteristics of the normal aging voice may cause speech to be mistakenly perceived to be related to a pathological condition such as dysarthria (Duffy, 1995). For example, Ryan and Burk (1974) reported that individuals judged to be older speakers could fall at the mild end of a “dysarthria continuum”. In a study employing the Frenchay Dysarthria Assessment to evaluate the speech production of 40 older adults (age range 54 – 82) with no reported history of neurological impairment, asthma, communication impairment, or oral or facial surgery, 80% of this elderly group were identified as having speech production characteristic of dysarthria (Wallace, 1991). Based on these observations, it appears that the resemblance of some of the features of the aging voice to those shown in dysarthric speech, e.g., vocal tremor, tension, breathiness, imprecise consonant articulation, and slow rate (Wallace, 1991), may result in the normal aging voice being misdiagnosed as “pathological” while the voice which is associated with a pathological condition, but with no other indicators, might be misdiagnosed as “just being old”.

Changes to voice and speech due to aging may reduce the ease of communication and affect quality of life by limiting social interaction. In a longitudinal study spanning five years, Verdonck-de Leeuw & Mahieu (2004) found that the 14 males (mean age 63, age range 51-81) in their study reported “avoiding a large party significantly more often after the time period of 5 years” (p.196). Roy, Stemple, Merrill and Thomas (2007) found that the elderly with voice problems “reported a wide array of undesirable voice effects on quality of life” (p.5) which included anxiety or frustration about their voice and of having to repeat what they said. Self assessments, i.e., the individual’s perception of their impaired voice, of voice-related quality of life (VRQOL) by people with age-related dysphonia were found to improve significantly when provided with voice therapy (Berg, Hapner, Klein & Johns III, 2008), highlighting the importance of age appropriate voice therapy.

The distinctive perceptual characteristics of age related dysphonia, or presbyphonia itself, may also promote negative social responses when speech is perceived as “old” and may further promote unfair or negative stereotypical age judgements about an individual’s potential or position in society. Therefore, it is important to identify features related to the perception of an “old” voice as well as the underlying causes of these changes so that strategies for improvement through speech and voice therapy can be developed to enhance oral communication.

1.2 Rationale

The effect of aging on voice is noticeable from the high incidence of voice disorders exhibited by the elderly. Voice disorders affect approximately 3 to 9% of the general population (Roy, Merrill, Thibeault, Parsa, Gray, & Smith, 2004) while elderly patients make up between 12% (Shindo & Hanson, 1990) and 35% (Ward, Colton, McConnell, Malmgren, Kashima & Woodson, 1989) of clinical patients. In a recent epidemiological study of individuals older than age 65 years, Roy et al., (2007) concluded that “voice disorders are common among the elderly, with 29% of respondents reporting a current voice disorder” (p. 5). The higher prevalence of voice disorders in the elderly population as compared with the general population highlights the impact of vocal aging on voice function.

The study of aging voice, which is of clinical and scientific relevance on its own, has gained more importance as the size of the geriatric population is expected to increase.

According to NZ Statistics, individuals in the geriatric population, i.e., people over age 65, comprised about 13 percent of all New Zealanders in 2009. It is projected that the percentage of geriatric individuals in the population will continue to increase in the coming decades, reaching around 20 percent by the late 2020s and to about 25 percent of the population by the late 2050s (Ashley-Jones, 2009). In view of the projected increase in the number of people in the geriatric age group and the higher incidence of voice disorders in the elderly, we can expect to see an increase in the need, demand, and expectation for evidence-based management of the aging voice supported with age-appropriate therapy.

Acoustic and physiological measurement of the voice have been found to yield information allowing for objective and quantitative voice assessments useful for monitoring subtle changes in the voicing mechanism to help differentiate between normal and pathological conditions or to provide feedback on the implementation of a specific therapeutic strategy. To gain an advantage from the more recent and advanced digital technology and fill the knowledge gaps in the assessment of aging voice, this study adopts a simultaneous cross-system instrumental approach to establish the voice profile of the normally aging voice and investigate the effect of some commonly used voice facilitating strategies. A literature review will be provided in the next chapter to identify the knowledge gaps in the understanding of vocal aging and the use of instrumental measures in the voice assessment of aging voice.

Chapter 2. LITERATURE REVIEW

This literature review describes the theoretical framework and previous findings relevant to the understanding of the aging voice, and to the justification of the instrumental measures employed and the facilitative technique chosen for investigation in this study.

2.1 The Aging Voice

The auditory-perceptual signs of vocal aging have been described in reports of the phonatory characteristics of the elderly and empirical studies of the perception of the aging voice.

2.1.1 Phonatory Characteristics of the Elderly

Elderly speech has been found to exhibit greater vocal instability (Gorham-Rowan & Laures-Gore, 2006), vocal tremor (Ryan & Burke, 1974), imprecise consonants *(*Ryan & Burke, 1974; Hartman & Danhauer, 1976), and slower rates of articulation (Ryan & Burke, 1974; Ramig & Ringel, 1983; Linville, 1996). Duffy (1995) described normal aging speech as having changes that are perceptually detectable with changes in pitch, voice quality, rate and prosodic variations, which are also characteristics similar to the salient features found in some forms of dysarthria. Colton and Casper (1996) described geriatric speech as being characterised by hoarseness, low pitch, imprecise articulation, breathiness, and long pauses. Honjo & Isshiki (1980) found that the voices of older women were perceived as being more rough and hoarse when compared with those of younger women. In general, the phonatory characteristics of the elderly include changes to pitch, albeit with a gender difference (Hartman & Danhauer, 1976; Hartman, 1979; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006), as well as reduced loudness

(Linville, 1996) and increased harshness (Hartman & Danhauer, 1976; Hartman, 1979; Linville, 1996) or breathiness (Ryan & Burke, 1974; Hartman & Danhauer, 1976; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006).

It is noteworthy that the reduced speaking rate often found in elderly speech may be related to changes in respiratory rate and speech breathing with age for adults. For example, the respiratory changes associated with aging have been found to be characterised by larger numbers of breaths taken and longer breath pause durations during speech (Hoit & Hixon, 1987; Shipp, Qi, Huntley, & Hollien, 1992), suggesting a need for the elderly to constantly replenish breaths to compensate for reduced breath support during phonation. As an adequate aerodynamic force is required to maintain the periodicity of vocal fold vibration, it is likely that reductions in loudness and phonatory stability often found in the aging voice may be related to the reduced respiratory power in the elderly.

The phonatory characteristics of geriatric speech have been associated with the physical changes that aging has on all parts of the respiratory, laryngeal, and articulatory systems. The course of the normal aging process can vary significantly among individuals and the degree to which this process affects phonatory characteristics may ultimately be more dependent on the general physical condition than on the chronological age of the speaker (Ramig & Ringel, 1983; Mathieson, 2001).

A voice may be considered disordered "when a person's quality, pitch and/or loudness differs from those of similar age, gender, cultural background, and geographic location" (Stemple, Glaze & Gerdeman, 2000, p.2). Because of the nonlinear relationship between chronological and physical aging, and the changes to phonatory characteristics with age for adults as discussed above, the question is raised as to when normally aging speech and/or voice should be considered disordered or dysfunctional. The extent to which phonatory characteristics are considered disordered or dysfunctional is in part dependent upon the degree of variation from the norm and the speaker's reaction to the variation. For example, if F0 increases from 100 Hz to 130 Hz, one elderly male may seek therapy because he considers it to be dysfunctional, while for another elderly male it may be a non-issue. A real cconcern, as presented in the Chapter 1 Introduction, is that a normal aging voice could be misdiagnosed as "pathological" while a voice which is associated with a pathological condition but has no other indicators might be misdiagnosed as "just being old".

2.1.2 Perception of Aging Speech and Voice

Despite considerable variations in the aging process and thus high variability in the geriatric voice, studies have shown that listeners are capable of differentiating between young and old voices and making good estimates of a speaker's age (Ptacek & Sander, 1966b; Shipp & Hollein, 1969). A variety of listener and speaker-related factors have been studied in relation to the perception of age.

2.1.2.1 Listener Effect

Both trained and untrained listeners have been found to be able to judge age when presented with speech and/or voice samples. In an auditory perceptual study, Ptacek and Sander (1966b) presented sustained vowel phonation and reading speech samples to 10 listeners, who were graduate students in speech pathology, and asked them to classify the samples as being either under age 35 or over 65 years. The vowel samples were recorded from 18 male (age range = 18-34 years; Mean = 25.1 years) and 18 female (age range = 18-27 years; Mean = 20.9 years) young speakers and 18 male (age range = 67-87 years; Mean = 76.2 years) and 18 female (age range = 69-87 years; Mean = 75.8 years) old speakers while the reading speech samples were from 9 male (age range = 19-23 years) and 9 female (age range = 20-21 years) young speakers and an older female and male speaker group similar in age to those from whom the sustained vowel phonation samples were obtained. It was found that listeners were able to perform the age classification task with a high rate of accuracy, showing an average accuracy rate of 99% when judging reading speech samples and 78% when judging sustained vowels. Shipp & Hollien (1969), in investigating the effect of physical aging on the perception of age in the male voice, found that young adult listeners, students aged 20-30, were able to judge a speaker's age along a 70 year continuum with a high degree of accuracy.

Listener age and gender have been found to influence their ability to judge a speaker's age. Untrained younger listeners tended to underestimate the age of older speakers (Shipp & Hollien, 1969; Hartman, 1979). In examining the effect of a listener's gender on age estimations using naïve adult listeners under age 30 years, Hartman (1979) found that females were consistently more accurate than males in judging age, particularly in judging voices of speakers after their fifth decade (i.e., over age 40 years). However, elderly women listeners (age range = 65-90 years) were found to be less accurate in estimating speaker age than younger listeners (Linville & Korabic, 1986). In an investigation of how listener's age could influence their ability to judge a speaker's age, Huntley, Hollien, & Shipp (1987) employed a direct magnitude age estimation method and asked 120 inexperienced listeners to judge, based on the reading of the third sentence of the Rainbow Passage, the ages of 105 healthy male speakers (age range = 20-90 years), who were divided by age into seven equal 10-year age groups. It was found that the two middle groups, including the young (age range = 20-30 years) and middle-aged (age range = 40-50 years) listener groups, made better estimates of the speaker's chronological age than the adolescent (age range = 9-15 years) and older adult (age range = 60-84 years) listener groups. These findings suggest that female adults and young mature adults perform better in estimating age.

2.1.2.2 Speaker Effect

While the aging voice is perceptually distinguishable from younger voices, the accuracy of age discrimination is affected by the type of speech sample presented and the age range of the speakers to be classified. For example, Ptacek and Sander's (1966b) study, described previously in Section 2.1.2.1, found the accuracy of age classification to be higher for reading samples than for sustained vowel phonation. Shipp and Hollien (1969) reported a greater agreement among the listeners in classifying speech samples between the youngest and oldest age speaker groups than in classifying those in the middle age range, suggesting a greater observable perceptual difference between the youngest and oldest speaker groups. These findings indicate that the auditory-perceptual signs of aging include suprasegmental features, which could be revealed in reading samples rather than in sustained vowel phonation, and may be more distinguishable in the older elderly. Studies related to age discriminating features and speech rate are reviewed as follows.

2.1.2.3 Age Discriminating Features

A general consensus has been found in the literature regarding the speech characteristics which enable listeners to identify geriatric speech with a high degree of accuracy. Ptacek & Sander (1966b) reported that the features judged to best differentiate the old (older than 65 years) from the young speaker groups (under age 35 years) were a slower speech rate, greater hesitancy, hoarseness, lower and less varied pitch, and less vitality and intensity. In a study of perceived age estimates based on the voice of 80 healthy adults between the ages of 40 and 80 years, Ryan and Burk (1974) identified air loss, imprecise consonants, and slow rate of articulation as strong discriminators of elderly speech. In a study on the perceptual features in the speech of males across four age decades, including the 20s, 30s, 40s and 50s age groups, 20 trained listeners, who were speech therapists, were asked to judge 30-second samples of continuous speech and identify salient perceptual characteristics across the age groups (Hartman & Danhauer, 1976; Hartman, 1979). The five most prominent features that were reported to best discriminate between the youngest and oldest speaker groups were (1) high pitch, rapid rate, precise articulation, clear quality, and hypernasality in the youngest group and (2) hoarseness, low pitch, imprecise articulation, breathiness, and slow rate in the oldest group. These findings describe aging speech as generally being characterized by deterioration in both voice quality and speech rate and clarity.

Changes in speech rate, particularly when it is slowed, have been associated with older perceived age estimates in male speakers (Shipp et al., 1992). Harnsberger, Shrivastav, Brown, Rothman, & Hollien (2008) found speaking rate to be a significant cue in the perception of age. When speech rate was increased by 20% by resynthesising the reading samples of the Rainbow Passage recorded from male speakers (age range = 74-88 years; Mean real age = 82 years), the speech sample was judged to be younger than the original speech sample. In addition, speakers who were perceived to be "old" were found to produce speech at a rate significantly slower than those perceived to be “young”. In older male speech samples, the average perceived age was found to decrease when the speaking rate increased through resynthesis (Mean perceived age = 68 years).

Hoarseness is regularly cited as one of the features of the elderly voice (Colton & Casper, 1996; Honjo & Isshiki, 1980; Linville, 1996) and that it distinguishes elderly from younger voices (Ptacek & Sander, 1966b; Hartman & Danhauer, 1976; Hartman, 1979). The increase of noise in the vocal signal is an indicator of hoarseness in the voice (Deal & Emanuel, 1978; Yumoto, Gould & Baer, 1982). In a study of 22 males and 20 females (age range = 19-60 years, Mean = 36 years) without laryngeal or pulmonary complaints and 12 males and 8 females (age range = 21-38 years, Mean = 46 years) with laryngeal complaints, Yuomoto et al., (1982) reported a significant positive correlation between harmonics to noise ratio (H/N) and spectrogram measurements and suggested that H/N may be useful in the clinical quantification of hoarseness. A discussion of signal-to-noise ratio and the geriatric voice is presented in Section 2.4.2.3.

The acoustic correlate of vocal pitch, i.e., fundamental frequency, has been found to characteristically decrease in females (Linville, 1996, 2002; Mathieson, 2001; Ferrant, 2002) but increase in males with age for adults (Hollien & Shipp, 1972). Listeners have been found to be able to distinguish young from old voices mainly based on speaker pitch (Hartman & Danhauer, 1976; Hartman, 1979; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006). Women were more often judged as being older when their pitch was lower (Linville & Fisher, 1985) and men were judged as older when their pitch was higher (Shipp, Qi, Huntley & Hollien 1992). However, Ptacek and Sander (1966b) reported that both female and male voices were perceived as older by 7 of 10 listeners (under age 35), when F0 was lower, suggesting that the gender specific relationship between pitch and perceived age may be overridden by other factors.

Breathiness is one of the the other well reported characteristics of the elderly voice (Ryan & Burke, 1974; Hartman & Danhauer, 1976; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006). A discussion of breathiness and aging is included in Section 2.4.3.3 Harmonic One–Harmonic Two (H1-H2) Amplitude Difference.

2.1.3 Summary

Research has reported that the speech and voice of older females and males are perceptually distinguished from that of younger adults, and even untrained naive listeners can make reliable estimates of age. As the chronological age of speakers increased, listeners were more likely to judge them as being older (Shipp & Hollein, 1969; Ryan & Burk, 1974). This would suggest that as the aging process progresses, speech and voice become more identifiable as "geriatric". Auditory perceptual parameters that appear to distinguish elderly from younger speech and voice include changes in pitch, reduced loudness, voice quality, and stability (e.g., increased hoarseness, tremor, roughness, and breathiness), imprecise consonants, and slower speech rate (e.g., increased number of breaths and longer breath pauses).

2.2 Anatomical and Physiological Changes in Vocal Aging

The apparent ease at which listeners are able to distinguish elderly from young speech and voice samples indicates the presence of an effect the normal aging process has on the voicing mechanism. This audible voice change due to aging is most likely to be related to the broad anatomical and physiological age-related changes which affect all parts of the vocal system, resulting in respiratory, laryngeal, and supraglottal vocal tract changes.

2.2.1 Respiratory Changes

The respiratory system provides the aerodynamic force (i.e., subglottal pressure) needed to set the vocal folds into vibration and initiate phonation. When alterations to this system occur as a result of physiological aging, consequences to phonation can be expected. The respiratory system is affected by the aging process, with reported structural changes such as calcification of the rib cartilages which limits movement of the thoracic cavity (Luchsinger & Arnold, 1967), a lowering of the lungs in the thorax (Mathieson, 2001), and reduced tissue elasticity (Morrison & Rammage, 1994). Changes to the respiratory function due to aging include decreases in respiratory volume (Morrison & Rammage, 1994) and reduced respiratory (or breath) support (Awan, 2006). Reduction in breath support may be the result of various age-related changes which may include reduction in pulmonary recoil pressure, lung and thoracic cavity size, respiratory muscle force, and a loss of elasticity in the lungs (Awan 2006).

Vital capacity, the amount of transitional air used for inspiration and expiration, and residual volume have been found to alter with age for adults. Although total lung capacity itself remains constant throughout adulthood (Hoit & Hixon, 1987), residual volume, which is the amount of air remaining in the lungs after maximum exhalation, increases with age for adults (Mathieson, 2001), resulting in a decrease of vital capacity, the maximum amount of air available for a person to expel from the lungs after a maximum inspiration. A reduction of vital capacity in older populations has been consistently demonstrated (Hoit & Hixon, 1987; Hoit, Hixon, Altman, & Morgan, 1989; Sperry & Klich, 1992). For example, Hoit & Hixon (1987) found vital capacity and residual volume to differ significantly with age for male adults in a comparison of three age groups: 25+, 50+, and 75+. In a follow-up study, Hoit et al. (1989) examined respiratory function in females using three age groups, 25+, 50+, and 75+, to match the age groups used for the male participants in the Hoit & Hixon (1987) study and found similar results. Based on these findings, it appears that the aging effect on the respiratory function show similar patterns for males and females.

Control of the expiratory air stream during phonation relies on vocal fold adduction and adequate laryngeal resistance. Melcon, Hoit & Hixon (1989) found that males aged 75+ showed lower laryngeal resistance values than younger males and attributed these findings to an increase in airflow for this age group. In other words, lower laryngeal resistance may result in greater loss of air during phonation, reducing the amount of available expiratory air needed for phonation. One means of describing the efficiency of expiratory air during phonation is a measure of the number of syllables in each breath group. Examination of age-related changes in the number of syllables per breath group was shown to reduce with age for both men and women (Hoit & Hixon, 1987; Hoit et al., 1989). According to Hoit et al. (1989), the reduction in the number of syllables per breath group in the elderly may be related to the reductions in laryngeal valving due to aging.

2.2.2 Laryngeal Changes

The aging larynx is visually different. When observed through laryngostroboscopic examination, the presbylarynx is characterized by vocal bowing, prominence of vocal processes, and spindle-shaped glottis chinks (Pontes, Brasolotto, & Behlau, 2005). The anatomical and physiological changes in the larynx due to aging include tissue changes to the form and structure of the laryngeal glands which lubricate the vocal folds (Sato & Hirano, 1998), ossification of cartilaginous material (Luchsinger & Arnold, 1967; Kahn & Kahane, 1986; Morrison & Rammage, 1994; Colton & Casper, 1996; Hammond, Gray, Butler, Zhou, & Hammond, 1997; Mathieson, 2001) along with changes to the laryngeal articulatory joints (Kahn & Kahane, 1986), muscle fibre atrophy of the head and neck muscles, especially the intrinsic laryngeal muscles, and changes to the vocal folds and mucosa cover (Luchsinger & Arnold, 1967; Sato & Hirano, 1995; Mathieson, 2001), including collagen and elastic fibres losing their definition of structure and an increase in the amount of elastin in the intermediate layer of the vocal folds.

2.2.2.1 Laryngeal Glands

The laryngeal glands are located in several sites within the larynx, including those within the lamina propria of the vocal fold mucosa, the false vocal folds, and the ventricle, which is the space between the true and false vocal folds. These glands provide lubrication to the vocal folds as well as immunity protection. In autopsy examinations of five aged larynges (3 men and 2 women, ages 72-83 years) without organic disease of the larynx, Sato & Hirano (1998) found age-related morphological changes that might influence the amount, quality, and viscosity of the secretion of these glands. A reduction in laryngeal gland secretions would cause vocal fold dryness, which can then lead to irregular vibrations of the vocal folds and thus the deterioration of voice. Therefore, the reduction in secretions of the laryngeal glands due to aging may contribute to the signs of aging voice.

2.2.2.2 Laryngeal Cartilages

The thyroid, cricoid, and arytenoid cartilages have been found to undergo ossification and calcification with age. As ossification progresses, the cartilages harden and become less flexible (Kahane, 1987). The pattern of cartilage ossification varies considerably among people at similar chronological ages. For some people, the cartilages may begin to ossify early and start to lose their elasticity early in life, after the age of 25 (Mathieson, 2001). Ossification of the cartilages which often starts earlier in males than in females, is usually complete by the eighth decade of life (i.e., 70+) but may also complete by a time as early as the sixth decade (Kahane, 1987).

The ossification of laryngeal cartilages, particularly at the articulated joints, can disrupt the joint movement, speed, and balance required for phonation. Kahn & Kahane (1986) found evidence of extreme ossification in the cricoarytenoid joints (CAJ) in half of the dissections of six male aging (age range = 50-80 years) larynges. The changes included a thickening of the raised rim of the CAJ which would result in a diminished range of movement and thus incomplete glottal closure. As a consequence, there may be greater glottal insufficiency resulting in phonatory changes, such as reduced phonatory intensity or breathy voice, due to air leakage through the poorly approximated vocal folds.

2.2.2.3 Head and Neck Muscles

Muscle atrophy refers to a wasting away of muscle tissues, resulting in fewer muscle fibres in each muscle and thus reduction in muscle mass. Since the ability of a muscle to exert force is related to its mass, muscles become weaker as they atrophy with age in adults. Aging affects the head and neck muscles, including the extrinsic laryngeal muscles which control the vertical positioning of the larynx. The flaccidity and atrophy of the cervical muscles, including the sternocleidomastoid and trapezius muscles, along with their loss of elasticity and over-stretching of the ligamentous suspension apparatus, results in a permanent descent of the larynx (Luchsinger & Arnold, 1967). Indirect evidence of a lowering of the larynx with age for adults may be found in the age-related changes to the formant frequency measures since they are influenced by vocal tract size. Linville and Rens (2001) reported that a lowering of the formant frequencies in the elderly population could be an indication that aging results in a lengthening of the vocal tract. The authors suggested that the greater degree of aging-induced formant frequency lowering found in woman than in men might be due to a greater weakening of laryngeal soft tissue support (ligaments and strap muscles) in women.

2.2.2.4 Intrinsic Laryngeal Muscles

The intrinsic laryngeal muscles, including cricothyroid (CT), thyroarytenoid (TA), posterior cricoarytenoid (PCA), lateral cricoarytenoid (LCA), and interarytenoids (transverse and oblique), control the tension and vibratory properties of the vocal folds. All intrinsic laryngeal muscles are innervated by recurrent laryngeal nerve except for CT, which is innervated by the superior laryngeal nerve. Damages to the laryngeal nerves have been shown to affect glottal closure, demonstrating the link between the intrinsic laryngeal muscles and vocal fold approximation or glottal configuration. As a higher incidence of glottal incompetence can be seen in elderly men and women (Luchsinger & Arnold, 1967; Morrison & Rammage, 1992; Linville, 1996; Ferrand, 2002), atrophy of the intrinsic laryngeal muscles may be one contributing factor to the signs of an aging voice.

Electromyography (EMG) is a technique used to record the level of electrical activity produced by muscles when they are activated through electrical stimulation or through neurological stimulation. Amplitude peaks in EMG measurements reflect the number of motor units activated. A reduction in EMG activity has been reported for the muscles of older individuals. Baker, Ramig, Sapir, Luschei & Smith (2001) used EMG to measure the muscle activity of TA, CT, and LCA, which are mainly vocal fold adductors, in 4 young adults (2 women, 2 men), aged between 24 and 28 years, and 5 older adults (1 women, 4 men), aged between 68 and 79. They found that EMG values tended to be lower and more variable for the older adults than for the young adults, and that this trend was most apparent for the TA muscles. As atrophy of the vocalis muscle, namely, the internal TA muscle, may not only reduce vocal fold tonicity but also impair its ability to control the shape of glottal configuration, a reduction in the efficiency of laryngeal valving in the elderly may be a reflection of this muscle atrophy (Mathieson, 2001).

2.2.2.5 Vocal Folds

The vocal folds are composed of multiple tissue layers, each of which is vulnerable in different ways to the aging process. The upper layer consists of stratified squamous epithelial tissue and sits directly on top of the connective tissue structure, the lamina propria. The lamina propria itself consists of three layers: (1) the superficial layer, which is composed of loose fibrous material and is gelatinous in consistency (Hirano & Sato, 1993), (2) the intermediate layer, which is mostly composed of elastin fibres, and (3) the deep layer, which is primarily composed of collagen fibres. The epithelial layer and the superficial layer of the lamina propria are jointly referred to as the mucosa. The intermediate and deep layers of the lamina propria are known collectively as the vocal ligament and are positioned just above the vocalis muscle, or internal TA muscle. With age, the layers of the vocal folds undergo structural changes. Each of the vocal fold layers undergoes the aging process differently, with each contributing to an overall cumulative aging effect on the vocal folds which ultimately affects the vibratory patterns of the vocal folds.

2.2.2.5.1 Changes of Elastin Fibers

The elastin fibres in the superficial and intermediate layers of the lamina propria show visible signs of change with age. Specifically, the superficial layer becomes more oedematous and the concentration of the elastin and collagen fibres in the vocal ligament changes in the aging larynges. Sato & Hirano (1997) found, in a study of cadaver larynges, morphological changes to the elastin in the superficial layer in older larynges. Elastic fibres in younger samples were found to be aligned, parallel to vocal fold length, with branches forming loose networks. In contrast, the elastic fibres in the superficial layer of older larynges were found to be more varied in size and more disorganised, forming more complex networks and showing rougher surfaces. Other observed aging-related changes included an increase of amorphous substances and a decrease in the number of microfibrils. Microfibrils are important for the development of new elastic fibres. In a study that compared paediatric, adult, and geriatric excised larynges, Hammond et al. (1997) reported increased elastin concentrations with age for adults. Additionally, there was a marked upward shift of the intermediate layer resulting in a reduction in the size of the superficial layer. As the border between the superficial and intermediate layers was defined as the location where elastin concentration had the largest increase, the authors suggested that a shift of the elastin concentration toward the superficial layer would result in a thinner superficial layer and a shift of the vocal ligament closer to the epithelium and thus might be related to the decreased mucosal wave properties often observed in the geriatric population.

2.2.2.5.2 Increase of Collagen Fibers

Collagen, though predominantly found in the deep layer of the lamina propria, is also present in the superficial and intermediate layers. The importance of collagen and the reticular fibres lies in their ability to provide tensile strength (the resistance to break under tension) and resilience, as well as serving as a stabilizing scaffold in the extracelluar matrices of the vocal fold mucosa. Hirano, Kurita & Sakaguchi (1989) observed that an increase in the number of collagen fibres would result in a thickening of the deep layer. In a study of the superficial layer of 10 excised larynges from the elderly (5 female, 5 males, age range = 70-97 years), Sato, Hirano & Nakashima (2002) found that collagen in the thin superficial layers, particularly those of the male larynges, underwent several structural changes, showing an increase in number and density, an increase in fibre diameter, and greater irregularity in shape (showing twisted fibers). In addition, the number of reticular fibres in the superficial layer was found to decrease. Sato et al. (2002) noted that ”geriatric changes in the fine structure of the superficial layer of the lamina propria are one of the important causes of the voice’s changes with age” (p. 19).

2.2.2.5.3 Decrease of Fibroblasts

The creation of new fibrous components (both collagen and elastin) in the vocal fold mucosa is reduced as a result of aging-related degeneration of fibroblasts in the maculae flavae. The maculae flavae are small structures in the vocal folds responsible for controlling the synthesis of fibrous components. In their investigation using 10 cadaver larynges (5 males ages 71-93 and 5 females ages 72-87), Sato & Hirano (1995) found a reduction in the number of fibroblasts in the older larynges compared with younger adult ones and suggested that this decrease might indicate a reduction in the synthesis of the fibrous components in the vocal fold leading to changes to the viscoelastic properties of the vocal folds.

2.2.2.5.4 Summary

As the vocal folds undergo structural changes due to the normal aging process, it is expected that these changes could ultimately affect vocal fold vibratory patterns. Biever and Bless (1989) found that aperiodic vocal fold vibration was present in 85% of the 20 healthy geriatric female voice patients (age range = 60-77 years) included in their study. A majority of these cases exhibited changes in the amplitude of vocal fold mucosal wave and a small number of cases showed some degree of stiffness in one or both of the vocal folds. These findings supported a potential link between the structural change of the vocal fold layers and vocal fold vibration in the aging voice. A gender difference in vocal aging has been noted, however, by Abitbol (2006), identifying the main structural changes to the vocal fold layers due to aging as being associated, in males, with shortening of the vocal ligaments, thinning of the intermediate layer of the lamina propria (due to loss of elastic fibers), atrophy of the deep layer of the lamina propria, and fibrosis and, in females, with thickening of the mucosal covering of the vocal folds and loss of elastic fibers.

2.2.2.6 Hormonal Change

The two female hormones, progesterone and estrogen, and the male hormone, androgen, underwent changes in females after menopause. The changes in hormonal levels as a result of menopause included a cessation of progesterone, a reduction in estrogens, and the appearance of androgen (Abitbol, Abitbol & Abitbol, 1999). These hormonal changes alter the physical characteristics of the vocal folds and consequently affect phonation (Sataloff et al., 1997; Abitbol et al., 1999; Gorham-Rowan & Laures-Gore, 2006).

Reduced estrogens and increased androgens are responsible for an increase in vocal fold mass (i.e., they become oedematous), which may result in alterations to the vocal fold depth and contour (Biever & Bless, 1989) and the lowering of vocal pitch (Mathieson, 2001). In a study of 88 men and 122 women over the age of 60 years with voice complaints, Pontes et al. (2005) reported that the increase in vocal fold mass was more prominent in women, with 28.7% of women and 6.85% of men showing signs of increased vocal mass. After menopause, vocal fold mass tends to increase as the tissues become oedematous (Mathieson, 2001). In comparing three groups of healthy women, including young (Mean age = 25 years), middle-aged (Mean age = 50), and elderly (Mean age = 77), Ferrand (2002) found a significantly lower average F0 in elderly women than in the middle-aged and young women, and attributed this change in F0 to the presence of oedema as a result of postmenopausal changes.

Along with a lowering of fundamental frequency (F0), alterations to vocal fold shape or configuration as a result of hormonal changes may contribute to the irregularity of vocal fold vibration leading to the perceptual identification of a voice as being elderly. In addition, reduced estrogen levels may also result in substantial changes in the mucous membranes of the vocal tract (Sataloff et al., 1997). Abitbol et al. (1999) describes the vocal menopausal syndrome as being "characterised by lowered vocal intensity, vocal fatigue, a decrease in range with a loss of the high notes and a loss of vocal quality" (p. 425). Gorham-Rowan & Laures-Gore (2006) found an increase in hoarseness in the voices of post menopausal women and related it to an increase in vocal fold mass and drying of the laryngeal mucosa due to the hormonal changes after menopause. Ferrand (2002) suggested that hormonal changes contributed not only to a lowered F0 in elderly women but also to the less efficient functioning of the laryngeal system leading to a reduced harmonic-to-noise ratio in the voice.

2.2.2.7 Incomplete Glottal Closure Patterns

A commonly observed feature of the aging larynx, which might be caused by tissue changes in the lamina propria (see Section 2.2.2.5 Vocal Folds), osscification of the cartilages at the CAJ (Kahn & Kahane, 1986) (see Section 2.2.2.2 Laryngeal Cartilages), and muscle fiber atrophy (see Section 2.2.2.4 Intrinsic Laryngeal Muscles), is incomplete glottal closure during the close phase of the vibratory cycle. Luchsinger & Arnold (1967) described the shape of the glottis in the elderly as often having "a bowed appearance during phonation which reflects the atrophy of the internal vocalis muscle" (p. 136). Linville (1996) described the effect muscle fiber atrophy of the intrinsic laryngeal muscles has on glottal configuration, indicating that atrophy of the TA muscle "might result in incomplete closure from the vocal processes to the anterior commissure (a spindle configuration), whereas, weakening of the interarytenoids would result in a posterior chink" and that "more generalized weakness affecting all adductor muscles might produce incomplete closure along the entire length of the glottis" (p. 1209). Deterioration of the cricoarytenoid joint may also contribute to the existence of glottal gaps by preventing complete adductory movement of the arytenoid cartilages. If vocal folds do not approximate completely in the closed phase of the vocal fold vibrating cycles during phonation, the gap between the folds may result in an excess of air passing through the glottis causing a breathier voice. The physiological changes in the lamina propria, cartilage, and muscle fibres resulting in glottal irregularities, may affect vocal fold vibratory patterns thereby producing a voice that may be low in volume and possibly hoarse.

The configuration of glottal gaps in women has been found to be different in different age groups. In elderly women, the glottal gap is more often located anteriorly or mid-membranously (Biever & Bless, 1989). In younger women, the glottal chink is more often found in a posterior position (Linville 1992). According to Linville (1992), the smaller incidence of posterior glottal gaps found in the elderly women, as compared with younger women, was unexpected as the age-related ossification of the cricoarytenoid cartilage (Kahane, 1980) and erosion of the CAJ (Kahane, 1988) would tend to inhibit adduction, thus creating a posterior gap. Oedema of the folds has been suggested as one explanation for the absence of posterior glottal gaps in elderly women. However, oedema was not found on visual examination of the vocal folds. Linville (1992) suggested that the posterior gap may be a functional behaviour in young women to achieve a "breathy" voice and that this behaviour is abandoned in older women. Linville (2002) found that elderly women exhibited greater variations than younger women in the control of glottal configuration, including the location of the gap and the degree of glottal closure, across pitch and loudness levels.

The occurrence of bowing and glottal gaps in females and males was found to differ both in the frequency of occurrence and in the age of appearance. Women tend to have a higher incidence of glottal gaps starting from a younger age through to old age. For men, glottal gaps tend to appear more in the elderly. The presence of an incomplete glottal closure was considered a normal feature in female vocal fold configuration (Soderstein &

Lindstad, 1990) regardless of age (Biever & Bless, 1989). In a study of young adults (9 women and 9 men, ages 20-35), Sodersten & Lindstad (1990) found incomplete glottal closure in 94.5% of the young women but in only 37.5% of the young men. The incidence of glottal gaps in females tends to remain steady, showing no noticeable change with age for adults (Linville, 2002). In a study of 20 young women (Mean age = 25 years) and 20 geriatric women (Mean age = 69 years), Biever and Bless (1989) found that 90% of the older women and 80% of the younger women exhibited glottal gaps. Linville (1992) found a similarly high occurrence of glottal gaps in both older and younger females, with a 83% occurrence rate in a group of young women (Mean age = 22.6 years) and 74% in a group of older women (Mean age = 76.4 years).

While the incidence of glottal gaps remains high for both young and elderly women, elderly men appear to have a significantly higher occurrence of glottal gaps than younger men (Honjo & Isshiki, 1980; Sodersten & Linsdsted, 1990; Linville, 2002; Pontes et al., 2005). In addition, upon laryngoscopic vocal fold examinations of 88 men and 122 women over the age of 60 who presented with voice complaints, Pontes et al. (2005) found that the incidence of glottal gaps was higher in elderly males than in elderly females. Specifically, Pontes et al. (2005) found that 19.7% of women and 29.5% of men showed vocal fold bowing, 36.9% of women and 38.6% of the men showed membranous spindle chinks, and 27.1% of women and 33% of men showed prominence of vocal processes.

2.2.2.8 Vocal Fold Discolouration

Another observable aging characteristic of the vocal folds is a change in colour. In healthy young adults, the vocal folds are generally observed to be white in appearance.

Discolouration of the vocal folds in healthy individuals has been associated with age for adults. Luchsinger & Arnold (1967) observed that the mucous membrane of the inner larynx normally appeared pale or reddish-yellow and that the normal whiteness of the vocal cords was replaced by brownish pigmentation in the elderly. Honjo and Issihiki (1980) reported a yellowish or dark greyish discolouration of the vocal folds in 39% of elderly men and 47% of elderly women (Mean age = 75 years) and attributed this discoloration to fat degeneration or keratosis of the mucous membrane. However, Linville, Skarin, and Fornatto (1989) studied 20 healthy women (age range 67-86 years; Mean = 76) and found no difference in vocal fold colour. They proposed that differences in judgments on the part of researchers of subtle changes in laryngeal appearance could have contributed to the conflicting findings between their study and that of Honjo & Issihiki (1980).

2.2.3 Vocal Tract Changes

The vocal tract, the airway above the glottis, acts as the resonating chamber for voiced sounds. As changes in the vocal tract due to aging have been observed, the effects of physical aging on the vocal tract would be expected to affect the resonating features of the voice. One reported age-related vocal tract change is the increase in the length of the vocal tract as the larynx lowers in the neck with age. The lengthening of the vocal tract may occur as a consequence of the atrophy of the head and neck muscles (Luchsinger & Arnold, 1967) as well as the thinning of the intervertebral disks (Kahane, 1980), which may be more common in females who experience a greater loss of vertebral bone density (Linville & Rens, 2001). In an acoustic study of the aging effect on changes of vocal tract resonance, Linville & Rens (2001) found that the frequencies of the first three formants lowered for both elderly women and men (Mean age for females = 70 years, males = 71) as compared with younger participants (Mean age = 21 years), suggesting vocal tract lengthening in the elderly. Vocal tract lengthening was greater in elderly women than elderly men. One possibility for this gender difference suggested by the authors, is that women may undergo greater weakening of the soft tissue support system of the larynx (ligaments, strap muscles) with age for adults than men.

Xue & Hao (2003) examined the oral and pharyngeal lumina using the acoustic reflection (AR) technique in two groups of young and elderly females (Mean age for the young group = 22 years, elderly = 74) and two groups of young and elderly males (Mean age for the young group = 21, elderly = 71) to investigate possible age-related changes to these structures. Acoustic reflection uses "acoustic reflected signals to provide graphical representations of area" (p. 691). Specifically, an acoustic wave with a short duration is directed into the mouth, the wave reflected back is recorded, mapping the area of the oral and pharyngeal lumina through to the glottis showing distinct landmarks which can then be measured. In addition to the AR measurements, formant frequencies were measured from the long-term average spectra (LTAS) of CVC productions using nine vowels. Using the AR and the acoustic signals, Xue and Hao (2003) identified a number of vocal tract features characteristic of the elderly for both genders. These included (1) increase in oral cavity length and volume (2) significant increase in vocal tract volume (not significant for vocal tract length) and (3) similarities in aging patterns of acoustic changes of speech production, e.g., a consistent lowering of formant frequencies, especially the frequency of the first formant. Changes to oral cavity length and volume may have occurred as a result of changes to dentition including the loss of teeth and the introduction of dentures. It was suggested that these vocal tract changes can affect the articulatory proficiency of the elderly by disrupting life-long learned articulatory behaviours which may have to be relearned.

2.2.4 Summary

The aging effect on the anatomy and physiology of the respiratory, laryngeal, and articulatory systems was found in both females and males, with some gender differences observed mainly in the presence of glottal incompetence and changes in the vocal fold mass and vocal tract length. As the rate of age-related changes may vary greatly, it is difficult to argue for a definitive "vocal age" for people based on chronological age alone (Ramig & Ringel, 1983; Sataloff et al., 1997; Mathieson, 2001).

2.3 Normal Aging and the Neurologically Impaired Voice

Normal aging speech and voice have been found to exhibit some dysarthric characteristics, such as deviations of rate, imprecise consonants, harsh quality, low pitch, and shorter phrases. Neurological changes as a result of normal aging include neuron atrophy which is a common feature of aging in humans (Finch, 1993), increased breakdown of intact myelin with age for adults (Sloane, Hinman, Lubonia, Hollander & Abraham (2003) which affects the 'speed at which messages are transmitted between the brain and muscles' (p. 47) (Benninger & Murray, 2006). Suhara, Inoue, Kobayashi, Suzuki & Tateno (1993) reported an age-related decrease in the binding of acetylcholine receptors in the brains of 18 healthy males (18-75 years of age) over this age range. The decrease or destruction of the acetylcholine receptors in the neuromuscular junction, make muscles less responsive (Duffy, 1995). Dysarthria is a movement disorder often associated with pathology of the central and/or peripheral nervous system structures. Darley, Aronson & Brown (1969b), in a study of 212 patients sampled from seven discrete groups of neurological impairments with dysarthria, found that voice characteristics associated with the diagnosis of dysarthria included deviations of rate and loudness, imprecise consonants, strained and strangled and harsh quality, low pitch, and short phrases. Although there are some minor discrepancies in the research outcomes of the past six decades regarding the speech and voice characteristics of flaccid, spastic, ataxic, hypokinetic, hyperkinetic and mixed flaccid-spastic dysarthrias, abnormalities in F0, speech rate, vocal stability, and loudness are frequently reported as the vocal signs of dysarthria (Aronson, 1980; Colton and Caspar, 1996; Mathieson, 2001; Brookshire, 2003).

As mentioned previously, some characteristics of the normal aging voice are similar to the salient features of dysarthria (Duffy, 1995). Based on a perceptual study of voices obtained from 80 healthy elderly people, Ryan and Burk (1974) found that normal aging individuals had perceptual characteristics of vocal tremor, tension, breathiness, imprecise consonant articulation, and slow rate, with the severity of these signs falling within the mild end of the dysarthria continuum. In a similar study, Hartman & Danhauer (1976) presented spontaneous speech samples from healthy males, aged between 25 and 70 years, to 20 untrained listeners to determine the perceived age and found that the group perceived to be the oldest was characterized by hoarseness, low pitch, imprecise articulation, breathiness, and long pauses.

Other vocal features common to both normal aging and dysarthric individuals include vocal bowing and increased vocal instability. For example, vocal fold bowing, a typical characteristic of the aged voice is also found in individuals with Parkinson's disease

(Morrison & Rammage, 1992; Smith, Ramig, Dromey, Perez & Samandari, 1995; Mathieson, 2001). Increased vocal instability, as reflected acoustically in increased jitter (cycle-cycle frequency variation) and shimmer (cycle-to-cycle amplitude variation) and decreased signal-to-noise ratio (SNR), was found in both the aged and in individuals with neurological conditions (Ramig & Scherer, 1992). Increased jitter and shimmer and reduced harmonic-to-noise ratio (HNR) have been reported in patients with damage to upper motor neurons (pyramidal lesions) and lower motor neurons, while reduced HNR has been reported in patients with upper motor neuron (extrapyramidal lesions) and cerebellar lesions (Mathieson, 2001).

Although jitter, shimmer, and SNR measurements have been used to assess voices associated with different types of neurological impairments, the results of some studies have led researchers to question the usefulness of these acoustic measures as a tool for differentiating between neurologically impaired and healthy individuals or between different types of neurological disorders. For example, Kent, Kim, Weismer, and Kent (1994) found that none of the three clinical groups studied, which included amyotrophic lateral sclerosis, Parkinson's disease, and cerebral vascular accident, differed significantly from the control group (normal aging non-smokers aged between 65 and 85 years) on the four selected acoustic measures, including F0, jitter, shimmer, and SNR. Zwirner, Murry & Woodson (1991) found a high degree of variability in the acoustic parameters, F0, jitter, shimmer and SNR, and concluded that these measures were insufficient for differentiating between Parkinson's disease (hypokinetic), Huntington's disease (hyperkinetic), and cerebellar ataxia (ataxic).

Although dysarthric and aging speech and voice share many common speech and voice characteristics, their aetiology may be different. Dysarthria is mainly neurological in origin (Darley et al., 1969b). In contrast, the vocal signs of aging are more likely to result from fibre loss and muscle atrophy, histological changes (e.g., ossification of cartilaginous material), and hormonal changes (Luchsinger & Arnold, 1967; Morrison & Rammage, 1994; Sato & Hirano, 1995; Colton & Casper, 1996; Mathieson, 2001) although the aging effect on the cognitive process and neuromuscular control may also be involved (Torre III & Barlow, 2009). While the variability of acoustic measures within and among neurological groups is mainly due to the different rates of disease progression, the increasing variability in the acoustic measures of adult voice with age for adults may be more related to different rates of aging (Torre III & Barlow, 2009).

2.4 Acoustic Characteristics of the Aging Voice

Acoustic measures of voice provide objective measures that can be related to the subjective perceptual judgments. Ramig & Ringel (1983) suggested that acoustic measures may be better indicators of physical aging than chronological age alone.

2.4.1 Fundamental Frequency (F0)

Fundamental frequency is the number of times a complex waveform repeats itself per second, and is measured in Hertz (Hz). It is the acoustic correlate of vocal pitch. The F0 measure has been found to be sensitive to the aging effect, where it tends to decrease in elderly females (Linville, 1996, 2002; Mathieson, 2001; Ferrand, 2002) and increase for elderly males (Hollien & Shipp, 1972). Specifically, age-related gender differences on F0 are characterised by an upward shift in F0 for men and a downward shift for women after middle age (Biever & Bless, 1989; Brown et al., 1989; Linville et al., 1989; Higgins & Saxman, 1991; Colton & Casper, 1996; Linville, 1996, 2002; Mathieson, 2001; Ferrand, 2002). For men, F0 tends to fall during middle age and then rise as they age (Mysak, 1959; Hollien & Shipp, 1972). For women, F0 tends to lower as a consequence of menopause and remain steady afterwards (Colton & Casper, 1996). It has been noted however, that this group trend of F0 lowering in the elderly women may not apply to individuals as contradictory evidence demonstrating intersubject variability has been reported (Max & Mueller, 1996).

In general, the reason F0 shifts with age for adults may be due to the effect the normal course of physical aging has on individuals. Measures of F0 have been reported to be more variable in the geriatric population than in younger groups (Biever & Bless, 1989; Brown et al., 1989). The F0 changes due to aging have also been reported to show a gender difference (Hartman & Danhauer, 1976; Hartman, 1979; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006). As mentioned previously, the effect of aging on F0 in geriatric men (i.e., an increase) may be a consequence of atrophy of the vocalis muscle and changes to the lamina propria (see Section 2.2.2.4). The hormonal changes in women following menopause, i.e., the decrease in estrogen, a cessation of progesterone, and the appearance of androgen (Abitbol et al., 1999), cause a structural change to the vocal folds resulting in a decrease in F0 (see Section 2.2.2.6). Linville et al. (1989) suggested that the decrease in F0 may be due to either changes in the mechanical properties of the vocal folds or loss of respiratory control.

With advancing age, pitch range may become smaller as the process of calcification continues and the cartilages and muscles become less elastic (Kaplan, 1971). For elderly women, this may be expressed as a loss of the high tones (Brown et al., 1989) and a shift toward the lower frequencies as the vocal folds become thicker. For elderly males, atrophic changes within the vocal folds may result in the pitch range being shifted to higher pitch levels (Luchsinger & Arnold, 1967). Comparing the pitch range between young and elderly voices, Ptacek & Sander (1966a) found a statistically significant reduction in the total pitch range for older females and older males (Mean age = 76.9 for both gender groups) as compared with young females (Mean age = 23.5 years) and young males (Mean age = 27.6). Specifically, young males had a Mean pitch range of 34.5 semitones while older males only 26.5 semitones. Similarly, the average pitch range in semitones was 32.8 semitones for young females and 25.1 semitones for the older females

The amplitude of F0 has also been found to change with age for adults. Linville (2002) observed that "elderly men, like elderly women, demonstrated age-related increases in amplitude in the region of the F0" (p. 477). As for the stability of the F0 of vocal fold vibration, Linville (1996) stated that "increased age might bring about decrement of function that would result in increased instability of vocal fold vibration" (p. 192).

2.4.2 Phonatory Stability

The term "phonatory stability" refers to the regularity of vocal fold vibration from cycle to cycle. Perturbation measures are a collective term which encompasses three acoustic measures of phonatory stability to quantify the degree of short-term variations of vocal fold vibration. These acoustic measures include jitter, which is the cycle-to-cycle frequency variation of the acoustic time waveforms, shimmer, which is the cycle-to-cycle amplitude variation, and SNR, which is the ratio of the periodicity component of the acoustic signal to its aperiodic (noise) component. The lower the jitter and shimmer and the higher the SNR, the more stable the voice is considered. Phonatory stability, as often gauged through measures of jitter, shimmer, and SNR, has been observed to be susceptible to the aging process (Linville, 1996; Ferrand, 2002; Baken, 2005; Gorham-Rowan & Laures-Gore, 2006). These measures were also most commonly used in the voice clinic and reported in the literature for assessing voice quality. Therefore, these acoustic measures were employed in this study for the investigation of aging voice.

The literature on perturbation measures, particularly %jitter, has produced some contradictory findings (see Section 2.4.2.1 Jitter) which may possibly be due to the accelerated pace of changing computer technology over the past few decades. Analysis of acoustic signals requires a medium on which to record the voice and signal processing and measuring tools for acoustic analysis. Voice recording instrumentation and analysis software for extracting perturbation measures have changed over time with advances in computer technology. Prior to around 1990, voice recordings were first made on analogue tape and then digitised for analysis (Ramig & Ringel, 1983; Biever & Bless, 1989). In later studies, acoustic measures were often derived from signals obtained from high quality voice recordings using direct digitization at a high sampling rate (Xue & Deliyski, 2001; Ferrand, 2002; Gorham-Rowan & Laures-Gore, 2006; Ma & Yiu, 2006).

2.4.2.1 Jitter

Jitter is a measure of the cycle-to-cycle variation in frequency in the acoustic wave. A larger jitter value indicates a greater short-term variation in the frequency of the acoustic signal. Jitter has not been shown to be a reliable indicator of the aging differences in the geriatric voice, and research results regarding aging effects are less conclusive for jitter than for example F0 and shimmer. Research has shown contradictory findings, with some studies showing that jitter is not useful in detecting differences in the aging voice (Ramig & Ringel, 1983; Linville, 1987; Brown et al., 1989; Biever & Bless, 1989; Ferrand, 2002) and others showing differences in jitter between age groups (Wilcox & Horii, 1980; Orlikoff, 1990).

Ferrand (2002) found no significant differences in jitter among three age groups: young, middle-aged, and elderly adults. However, when the vocal folds were viewed stroboscopically, a significant age group difference could be found in the vibratory patterns of the vocal folds, with the elderly group showing increased aperiodicity, incomplete midmembranous glottal closure, mucosal wave alterations, and reduced amplitude of vibration. Brown et al. (1989) compared jitter ratio between young and elderly speakers at three loudness levels, namely, conversational, loud, and soft, and failed to find significant age differences. In a study of 20 geriatric women (Mean age = 69 years) and 20 young normal adult women (Mean age = 25), Biever and Bless (1989) reported that jitter was higher for the older group but also failed to find a statistically significant aging effect. In contrast, jitter was found to be significantly higher in older men than in younger men (Wilcox & Horii, 1980; Orlikoff, 1990). Ramig and Ringel (1983) found that health played a statistically significant role on measures of jitter, where individuals in poor physical condition showed greater jitter values in sustained vowel phonation as compared with healthy controls. The conflicting findings regarding the aging effect on the jitter measure suggests the need for additional research with considerations of confounding factors such as sample size and task.

2.4.2.2 Shimmer

While it remains unclear whether there is an aging effect on jitter, shimmer has been shown to better differentiate between young and elderly voices. In a study of 20 geriatric women (ages 60-77) and 20 normal adult females (ages 22-28), the average shimmer value was found to be significantly higher in the group of geriatric women than in the group of younger women (Biever & Bless, 1989). Orlikoff (1990) studied shimmer in three groups, healthy young males (Mean age = 30 years), healthy elderly males (Mean age = 73.3), and atherosclerotic elderly males (Mean age = 70.3). Shimmer was found to differ significantly between the group of young males and the two groups of elderly males (one healthy and the other atherosclerotic) but not between the two geriatric groups. In comparing three male age groups, namely, young (aged 35-45 years), older (45-55), elderly (65-75), Ramig and Ringel (1983) found shimmer to be significantly higher in the elderly group than in the youngest group. Ramig and Ringel (1983) also found that both age and physical condition had a significant effect on the shimmer values measured from sustained maximum phonation samples but not on those from vowels sustained for a comfortable duration.

2.4.2.3 Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio, or interchangeably termed as harmonics-to-noise ratio (HNR) or noise-to-harmonic ratio (NHR; the “reverse” of HNR), refers to an energy ratio between the periodic components and the noise components in the sound waves. A higher SNR indicates a greater energy level of periodic components relative to the noise components. Signal-to-noise ratio has been shown to be not only sensitive to the identification of aging effects (Xue & Deliyski, 2001; Ferrand, 2002; Gorham-Rowan & Laures-Gore, 2006) but also in judgements of voice quality (breathiness) (Yu, Ouaknine, Revis & Giovanni (2001), and in identifying effects of extended voice use (Gelfer, Andres & Schmidt, 1991; Kitch, Oates & Greenwood, 1996). Ferrand (2002) compared HNR and jitter in three groups of healthy women, including young (Mean age = 25 years), middle age (Mean age = 50), and elderly (Mean age = 70), and found HNR to be more sensitive to the aging effect than jitter, with the elderly group being associated with a lower HNR compared with the younger groups. Specifically, with measures derived from sustained phonation of the isolated vowel /a/ for about three seconds, a significant age difference was found between the elderly group and the two younger groups for HNR but not for jitter (Ferrand, 2002).

Similarly, in a study of 112 female and male healthy individuals, Gorham-Rowan and Laures-Gore (2006) found the elderly group (Mean age = 70 years, n = 56) to have a higher noise-to-signal ratios than the younger group (Mean age = 25 years, n = 56). Xue and Daliyski (2001) compared the NHR measures extracted from the voice samples of 44 elderly individuals (men and women aged between 70-80) with those from the normative data (young and middle aged adults) provided by the Multi-Dimensional Voice Program (MDVP; Kay Elemetrics) and found that the elderly speakers in average had a significantly higher NHR than the young and middle aged controls.

The consistent findings of a lower SNR or HNR or a higher NHR in the geriatric voice as compared with younger adults demonstrates the sensitivity of this measure in detecting the aging effect. The decrease in SNR with age for adults has been related to the adverse effect of aging on vocal function. Gorham-Rowan and Laures-Gore (2006) suggested that reduced respiratory efficiency as a contributing factor to the increased noise and instability in the elderly female voice.

2.4.3 Spectral Measures

With Fourier transform, a complex waveform can be decomposed into individual sinusoid waves with associated amplitude, frequency, and phase. A spectrum is a two-dimensional display of this waveform, with frequency in the x-axis and amplitude in the y-axis. As changes to vocal tract resonance, as well as voice quality, can be reflected in the energy distribution across frequencies, spectral measures have been used to quantify these changes. Spectral measures include measures of the frequency loci and amplitude of the selected peaks in a spectrum.

2.4.3.1 Formants One (F1) and Two (F2)

Formant frequencies, which are the frequency loci of clusters of spectral energy representing the resonant frequencies of the vocal tract, play a key acoustic role in vowel identification (Peterson & Barney, 1952; Hillenbrand, Getty, Clark, & Wheeler, 1995). The inherent differences in the frequencies of the first two formants (F1 and F2), which in practice define the identity of a vowel, relate to tongue location, including the height and frontness of the tongue. The frequency of F1 is inversely related to tongue height. For example, the high vowel /i/ is associated with a lower F1 than the low vowel /a/. The frequency of F2 is positively related to the “frontness” of the tongue position. In other words, the further front (anterior) the tongue bulge, the higher the F2 frequency. The frequency of F2 is further affected by the degree of lip rounding. Lip rounding extends the length of the vocal tract and thus lowers the frequencies of F2 and Formant three (F3).

The values of the first two formants, F1 and F2, are not static; they change with articulatory movements and with variations in vocal tract length. A change in vocal tract length as the larynx is raised or lowered, changes the dimensions of the resonating chamber and effectively changes its resonating frequencies. When the larynx is raised, it shortens the length of the vocal tract and results in a rising of the formants (Sundberg & Nordstom, 1976). As previously mentioned, vocal tract length increases with age for adults as the larynx lowers as a result of increased flaccidity and atrophy of the cervical muscles (Luchsinger & Arnold, 1967). Xue & Hao (2003) reported that the lowering of F1 frequencies found in a group of 38 healthy geriatric men and women were due to vocal tract lengthening as a result of aging. In an examination of the first three spectral peaks extracted from the LTAS of the first paragraph of the "Rainbow Passage", Linville and Rens (2001) found that the first peak, which is associated with F1, was significantly lower for both women (Mean age = 70 years) and men (Mean age = 71) compared to a younger group (Mean age = 21). The second and third spectral peaks, which are associated with F2 and F3 respectively, were also found to be significantly lower for females in the older group but only associated with a trend of lowering for the older males. They attributed the lowering of spectral peaks or formant frequencies to age-related vocal tract lengthening in conjunction with vowel articulatory changes.

Since formant frequencies reflect the vertical height and horizontal advancement of tongue during vowel production, they provide useful information regarding the dynamic as well as the structural changes to the vocal tract due to aging. Several studies (Endres, Bambach & Losser, 1971; Linville & Fisher, 1985; Linville & Rens, 2001) have shown that formants tend to lower in the speech of older individuals. A lowering of the formant frequencies as a function of age was reported in a longitudinal study by Endres et al. (1971), who measured changes of formant frequencies in 4 males (starting ages from 42 through 73) and 2 females (starting age for youngest female 29) over a 13-15 year period.

In a study of 75 women (age range 25-80), Linville & Fisher (1985) found that F1 and F2 were both significantly lower in older speakers than young speakers. In a study of formant frequencies obtained from the reading of the Rainbow Passage by 40 male speakers and 40 female speakers (20 in a younger group and 20 in an older group), Linville & Rens (2001) found that F1, F2 and F3 lowered by 29%, 10% and 9% respectively for the elderly women and by 11%, 2% and 2% for the elderly men respectively as compared with their corresponding younger comparison groups.

Formant frequencies vary when vocal tract length changes as a result of vertical laryngeal position movement and may be different for different vowels. Sundberg & Nordstrom (1976) measured the formant frequencies of vowels produced by two participants when the larynx was in both a raised and a lowered position; the change in laryngeal position in each direction was estimated at 1.5cm. They found that when length alone was considered, there was only a small effect on F1 for /i/ and /u/ but a larger effect on F1 for /a/. However, as a result of the change in vocal tract length (with either a raised or lowered larynx), changes in the formant F2 for /i/ was greater than the change occurring in /a/. As F1 is related to the vertical position of the tongue, the greater effect on F1 found in /a/ as a result of changes of vocal tract length may be related to the greater variations of jaw posturing for the production of /a/. As for the greater effect on F2 found in /i/ as a result of the dynamic change to vocal tract length may be related to the greater variations of tongue advancement for the production of /i/.

2.4.3.2 Vowel Space

The frequency values of the first two formants can be used to understand the articulatory movements associated with vowel production, providing an indirect assessment of the physiological changes in speech production. Using the F1 and F2 frequency values as coordinates (F1 on the x-axis and F2 on the y-axis) a vowel space graph can be plotted showing the relative acoustic differentiation among the vowels, providing a possible link to the perception of speech intelligibility. This section reviews the definition and the usage of vowel space in the literature.

2.4.3.2.1 What is Vowel Space

When the F1 and F2 frequencies of each vowel were plotted as two coordinates, the vowels shown at the corner of this F1-F2 plot are referred to as "corner vowels." These vowels represent the vowels with the longest between-vowel distance in F1 or F2 frequency and thus the greatest contrast of vowel identity. The vowel space is the area enclosed within the corner vowels. A more compressed vowel space has been associated with poorer vowel differentiation in terms of perception, or more restricted articulatory movements in terms of production. The vowel space can be constructed either as a triangle encompassing three corner vowels or a quadrilateral space using four corner vowels. The decision to use either a triangle or quadrilateral to illustrate the vowel space depends on the language or dialect being analyzed. The calculated size of the vowel space area has been shown to vary among different speaker populations. The analysis of vowel space area has also been used as a tool to investigate speech intelligibility in a wide range of conditions, including normal speech (Bradlow, Toretta, & Pisoni, 1996), voice disorders (Roy, Nissen, Dromey, & Sapir, 2009), speech disorders (Blomgren, Robb, & Chen, 1998), and neurological disorders (Weismer, Jeng, Laures, Kent, & Kent, 2001; Turner, Tjaden, & Weismer, 1995; Tjaden & Wilding, 2004).

2.4.3.2.2 Vowel Space Area and Speech Intelligibility

Investigations into the relationship between vowel space area and speech intelligibility in different speaking groups have linked the relative size of the vowel space area to perceptions of speech intelligibility. A larger vowel space is associated with better differentiation among vowels and thus higher speech intelligibility (Bond & Moore, 1994; Bradlow et al., 1996). Smaller vowel space areas have been associated with measures of lower speech intelligibility along with restricted articulatory movements, and have been reported for people with dysarthria (Weismer et al., 2001), stuttering (Blomgren et al., 1998), and voice disorders such as muscle tension dysphona (Roy et al., 2009).

The size of the calculated area of the vowel space has been used as one indicator to describe the intelligibility or clarity of a speaker's speech. In studies of normal speakers, a larger vowel space has been found to be positively correlated with better intelligibility. In a study using 200 listeners (10 listeners for each speaker) to judge the intelligibility of words produced by 20 speakers of General American English, Bradlow et al. (1996) found that vowel space dispersion (i.e., the average distance of the F1-F2 co-ordinates from the centroid point in the speaker's vowel space) and F1 range were significantly and positively correlated with overall sentence intelligibility. They concluded that speakers with large vowel spaces were generally more intelligible than speakers with reduced vowel space areas.

In studies that compared the vowel space areas of speakers with dysarthria with neurologically normal controls, the normal control group was found to have on average larger vowel space areas, which were also found to be associated with better intelligibility. Liu, Tsao, and Kuhl (2005) investigated the relationship between vowel space area and intelligibility by comparing a group of 20 young adult males with cerebral palsy (CP) (Mean age = 18.5 years) with 10 neurologically intact males who were matched for age. The males with CP were found to have smaller vowel space areas than the controls; the larger vowel space area was found to be associated with better intelligibility. In a study comparing the intelligibility of 19 healthy adults (Mean age = 71.1 years) with individuals with dysarthria secondary to two different neurological conditions, five female and five male patients (Mean age = 55.7 years) with amyotrophic lateral sclerosis (ALS), and one female and nine male patients (Mean age = 66.3 years) with Parkinson's disease (PD), Weismer et al. (2001) found that the vowel space area for the two dysarthric groups were smaller (i.e., more compressed) than that of the control group, although a statistically significant difference was only found between the male ALS group and the control group. At the beginning of the experiment and periodically during the experiment, the ten listeners were presented with a modulus representing 'average severity' speech samples from which comparisons were made with each of the speakers' sentences for rating purposes. The control group was found, in average, to show a higher intelligibility score than the two dysarthric groups, and vowel space area was found to be moderately correlated with the scaled intelligibility and severity ratings.

2.4.3.2.3 Vowel Space Area and Treatment Efficacy

An increase in vowel space area following treatment has been reported in a small number of research papers. Blomgren et al. (1998) measured vowel space area in three groups, untreated stutterers (Mean age = 28 years), treated stutterers (mean age = 27), and non-stutterers (Mean age = 35). A comparison of the vowel space areas among these three groups showed that the untreated group had the smallest vowel space area, followed next by the treated stutterers and then the non-stutters. Roy, et al. (2009) investigated the effect of manual circumlarygneal treatment (MCT) on vowel articulation in 102 women (Mean age = 46) with muscular tension dysphonia. Participants chosen for this study had to have shown improvement after one session of MCT and data of pre- and post-treatment readings of the second and third sentences of the Rainbow Passage were used for analysis. The authors found that the quadrilateral vowel space area increased significantly following MCT treatment. The two studies described above both report an expansion of vowel space area after treatment for stuttering and for treatment of muscular tension dysphonia

2.4.3.2.4 Vowel Space Area and Speech Rate

When speech rate slows, it has been shown that vowel space area increases along with greater distinction among vowels (Turner et al., 1995; Tjaden & Wilding, 2004). Turner et al. (1995) varied rate of speech (habitual, slow, and fast) in two groups of speakers, nine ALS patients and nine neurologically intact controls. As rates of speech slowed, both groups of speakers showed increased vowel duration averages along with the tendency for vowel space area to increase. Across changes in speaking rate, vowel space area changed more systematically for the control speakers than for the ALS group, which showed greater variations. In addition, it was found that the ALS group, in average, had a smaller vowel space area than the control group. Tjaden and Wilding (2004) investigated the effect of speaking rate and loudness on vowel space for 15 healthy controls and dysarthric patients, which included 15 speakers with multiple sclerosis (MS) and 12 speakers with PD. For the control group, vowel space area changed with all testing conditions but was largest when speech rate was slowed. Vowel space area also increased in the loud condition for the control group. For MS speakers, there was a significant difference in vowel space area between the habitual and slow speaking rates, with 11 of the 15 speakers showing an increase in vowel space area for the slow rate of speech. Vowel space area for PD speakers did not differ across conditions, i.e., neither for speech rate or intensity.

The impact of speech rate on vowel space area or speech intelligibility may be related to the speed of articulatory movement, and the precision of the articulator (e.g., the tongue) to reach its target position. In a study that measured the orofacial movements (of upper and lower lips, jaw, and tongue) of nine normal speakers (age range 24-54), McClean (2000) found that in slower rates of speech, the velocities of these movements decreased. This finding demonstrates that slower rates of speech are associated with slower articulatory movements. The findings of Turner et al. (1995) that for neurologically intact or ALS speakers there is an increase in vowel space area with a decrease in speech rate suggests that speech improvement may be facilitated through modification of speech rate in these individuals.

2.4.3.2.5 Summary

Vowel space area has been related to perceptions of speech intelligibility, where larger vowel space areas have generally been associated with greater speech intelligibility. The use of vowel space area as a measure has been found useful for differentiating between normal and some types of dysarthric speech (e.g., CP, MS, and ALS), demonstrating treatment efficacy (e.g., treatments for speakers with dysfluency or muscular tension dysphonia), and probing for effective facilitating strategies (e.g., modification of speech rate).

2.4.4 Harmonic One - Harmonic Two (H1-H2) Amplitude Difference

The acoustic spectrum provides information about the distribution of acoustic energy over a range of frequencies. Voiced sounds are associated with a spectrum having a clearly defined harmonic structure, starting with the first harmonic (H1), or termed F0, and its overtones. As voice deteriorates, noise components may replace some harmonics resulting in changes to the harmonic structure as well as to the shape of the spectral envelope and thus the spectral tilt (the decrease in amplitude in successive harmonic components in the spectrum), may also be affected by the vocal tract resonance. Spectral measures have been used as a tool in the investigation of voice quality. Klatt and Klatt (1990) found that the level of aspiration noise in the middle and upper portion of a spectrum and the amplitude of the first harmonic appeared to be related to judgments in breathiness. In particular, an increase in F0 amplitude has been attributed to an increased open quotient, which was associated with a relatively longer time the vocal folds remained open within each vibrating cycle and with greater transglottal airflow (Klatt & Klatt, 1990). The relative amplitude of the H1 has been shown to be correlated with perceptions of breathiness, with breathier voices associated with higher H1 amplitudes (Bickley, 1982; Ladefoged, 1983; Hammarberg et al., 1986; Klatt & Klatt, 1990; Hillenbrand et al., 1994; Hillenbrand & Houde, 1996).

Findings relating the effects of the characteristics of spectral tilt to perceptions of breathiness have reported different outcomes. Some studies have found a steeper spectral slope to be associated with breathiness due to the replacement of harmonics by aspiration noise in the mid frequency region (Hammarberg et al., 1986; Ladefoged et al., 1988; deKrom, 1995; Stevens & Hanson, 1995). Others have found a shallower spectral tilt to be associated with the perceived breathiness in normal females (Mendoza et al., 1996) or in individuals with unilateral vocal fold paralysis (Kim, Kakita, & Hirano, 1982; Hartl et al., 2001). As individuals with glottal inefficiency may compensate with supraglottal constriction, it is likely that vocal tract constriction, which may lead to the lowering of F1, may be a confounding factor that contributes to these conflicting findings regarding spectral tilt.

Breathiness is one of the well reported characteristics of the elderly voice (Ryan & Burke, 1974; Hartman & Danhauer, 1976; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006). Using LTAS, Linville (2002) found that both elderly females (Mean age = 70 years) and males (Mean age = 71 years) showed age-related increases in amplitude for F0 but that these changes were statistically significant only for females. When comparing the strength of the relationship between the perception of breathiness and various acoustic measures, the relative amplitude of H1 was found to be a better acoustic correlate of breathiness than spectral tilt (Hillenbrand et al., 1994). It appears that the relative amplitude of H1, defined as the difference between H1 and Harmonic two (H2) amplitudes (Klatt & Klatt, 1990; Hillenbrand et al., 1994), can be used to track changes of voice quality due to aging. An increase in the H1-H2 amplitude difference, which suggests a breathier voice, has also been associated with a voice produced with thinner vocal folds (Sundberg & Hogset, 2001; Stone, Cleveland, Sundberg, & Prokop, 2003) and thus may be used to reflect changes in vocal thickness as well as breathiness.

2.4.5 Voice Onset Time (VOT)

Voice onset time (VOT) is a temporal measure of the duration between the release of an unvoiced plosive (i.e., /p, t, k/) and the start of the glottal pulse for the following vowel. The control of VOT requires fine timing of motor adjustments both for the articulatory movements necessary for consonant production, and for the laryngeal movements and respiratory support needed to start phonation. Voice onset time has been found to be affected by rate of speech, with slower speaking rates associated with a longer VOTs (Miller, Green & Reeves, 1986; Kessinger & Blumstein, 1998). In studying a small group of young English speaking adults (Mean age = 23.8 years), Kessinger & Blumstein (1998) found that as speaking rate slowed, both VOT and vowel duration increased almost proportionally. Similarly, Miller et al. (1986) reported that when speaking rate slowed, syllable duration tended to increase and VOT increased significantly.

As described previously, the aging-induced motor dysfunctions, such as those related to muscle fibre atrophy to the intrinsic and extrinsic muscles (Luchsinger & Arnold, 1967) or lower and more variable muscle activities as reflected in EMG measures (Baker et al., 2001), may contribute to reduced speed in motor movements and thus slower rates of speech (Brown et al. 1989; Duffy, 1995; Linville, 1996). Since a slower speaking rate is one of the well recognised characteristics of elderly speech (Smith, Wasowicz, & Preston, 1987; Brown et al., 1989; Shipp et al., 1992), VOT would be expected to increase with age for adults. A longitudinal study of 20 male Dutch professional newsreaders, whose connected speech samples were taken with an average of 33.6 years between samples, showed that VOT increased with age for adults (Decoster & Debruyne, 2000) and that this increase was most evident in VOT measured from two consonant-vowel (CV), /pa/ and /ka/. In a study of 27 young adult (Mean age = 25.5 years) and 59 elderly (Mean age = 75.2 years) men and women, who were asked to produce 22 consonant-vowel-consonant (CVC) words (with six different vowels) embedded in a standard carrier sentence, Torre III and Barlow (2009) found that the average VOT measures for the older male group (i.e., /t/: 77 ms, /k/: 85 ms) were significantly shorter than both young female (i.e., /t/: 95 ms, /k/: 94 ms) and male groups (i.e., /t/: 95 ms, /k/: 99 ms) as well as the older female group (i.e., /t/: 100 ms, /k/: 105 ms).

A gender effect on VOT has been reported in some studies. In general, men were found to exhibit shorter VOT than women (Ryalls, Zipprer & Baldauff, 1997; Robb, Gilbert, & Lerman, 2005; Torre III & Barlow, 2009). In a study of 10 females (five Caucasian and five African American) and 10 males (five Caucasian and five African American) young adults (age range = 20-30 years), Ryalls et al. (1997) found VOT to be significantly shorter in males (i.e., /t/: 82 ms, /k/: 87 ms) than in females (i.e., /t/: 95 ms, /k/: 97 ms). In the Ryalls et al.(1997) study, six plosive consonants, /p/, /t/, /k/, /b/, /d/, /g/, with the vowels /i/, /a/, and /u/ formed CV words and some CVC words where no proper CV word existed. Using the same six consonants and three vowels in CV syllables embedded in a carrier sentence, Robb et al. (2005) compared 10 female and 10 male young adults (Mean age = 20 years) and found that males on average had a significantly shorter VOT (i.e., /t/: 76 ms, /k/: 78 ms) than females (i.e., /t/: 83 ms, /k/: 88 ms).

Some studies, however failed to find gender differences in VOT (Sweeting & Baken, 1982; Morris, McCrea & Herring, 2008). Sweeting and Baken (1982) compared three age groups (25-39, 65-74, and 75+), with five females and five males in each group, on the VOT measures obtained from CV words, including ‘beat”, “pete”, “bead”, embedded in a carrier sentence and did not find VOT to differ significantly by either gender or age. Nevertheless, Sweeting and Baken (1982) did find that VOT variability increased in the two older groups both within participants and between groups and concluded that the increase in variability of VOT measures reflected a reduction in articulatory stability as a function of age rather than fatigue. In a study of 40 female and 40 male young adults (aged range = 20-25 years) who produced CV syllables consisting of a plosive (/p/, /t/, /k/, /b/, /d/, and /g/) followed by a vowel (/i/, /a/, and /u/), Morris et al. (2008) found VOT did not differ significantly between females and males.

In summary, studies have reported mixed results for the age effect on VOT. In one longitudinal study (Decoster & Debruyne, 2000) VOT increased as males aged, while in the Torre III and Barlow (2009) study, VOT was shorter for older males, and, Sweeting and Baken (1982) reported no age differences for either females or males. Males however, were often reported to have shorter VOTs than females, both in younger and in older age groups. The differences in the VOT findings among studies may be related to methodological differences, such as differences in context (e.g., in isolation, carrier sentence, or spontaneous speech) and number of vowels used for the CV productions.

2.4.6 Speech Rate

A slower speech rate is one of the characteristics of aging speech (Smith et al., 1987; Brown et al., 1989; Linville et al., 1989). As mentioned previously, a slow rate of articulation is one of the five measurements (with the other four being voice tremor, laryngeal tension, air loss and imprecise consonants) found to be strong predictors of perceived age (Ryan & Burk, 1974). Research investigating the relationship between speaking rate and age has routinely found these two variables to be related. In general, it has been found that older people have slower rates of speech than younger adults (Ramig, 1983; Smith et al., 1987; Brown et al., 1989; Linville et al., 1989; Shipp et al., 1992). Brown et al. (1989) found a significant faster oral reading rate (obtained through reading of the first paragraph of the Rainbow Passage) in young women (Mean duration = 29 seconds) than in older women (Mean duration = 42 seconds). In a comparison of sentence speaking rate (defined as the number of syllables per second during oral reading of the third sentence in the Rainbow Passage) among three groups of males, young (aged from 21 to 35), middle-age (from 46 to 71), and elderly men (aged from 77 to 90), Shipp et al. (1992) also found speech rate to be significantly faster in the youngest group (Mean speaking rate = 5.29 syllables per second) than in the oldest group (Mean speaking rate = 3.69 syllables per second). In a group of healthy elderly women (aged between 67 and 86), Linville et al. (1989) reported a mean syllable reading rate of 4.87 syllable per second (ranging from 4.00 to 7.35 syllables per second) using the second sentence from the Rainbow Passage. Smith et al. (1987) compared age and speaking rates of combined groups of females and males under several speaking conditions, at a normal rate including monosyllabic words embedded in a carrier phrase, two-syllable “tongue-twisters”, and sentences. Participants were then asked to repeat the two-syllable words and tongue twisters at a self chosen faster rate, ensuring that accuracy was maintained. Speaking duration time in the elderly group (age range = 66-77 years) was found to be 22% longer in normal speaking conditions and 26% longer in fast rate speaking conditions as compared with the younger group (age range = 24-27).

In summary, it appears that speech rate tends to slow down with age for adults. However, it should be noted that age alone might not be the only factor to explain differences in speaking rate, as general health has also been found to affect speaking rate. For example, in a study of 48 men between the ages of 25-75, Ramig & Ringel (1983) found that a speaker's rate of speech might be dependent upon their general physiological condition.

2.4.7 Sound Pressure Level (SPL)

Sound pressure level (SPL) is the main acoustic correlate of loudness. Reduced loudness, along with slower rates of speech, greater hesitancy, less precise articulation, and longer duration of pauses, is one major characteristic of speech in the elderly (Linville, 1996). Research data have reported decreases in vocal intensity in aging voice in comparisons between young and older adults (Ptacek et al., 1966a; Linville, 1996; Baker et al., 2001; Hodge, Colton, & Kelley, 2001).

Ptacek et al. (1966a) asked adult females and males in two age groups (i.e., one below 40 years and the other over 65) to phonate the isolated vowel /a/ at maximum intensity for several seconds. A VU meter was used to gauge the intensity of the vowel productions. The older age group showed significantly lower SPL than the younger age group for both males (old males: 100.5 dB, young males: 105.8 dB) and females (old females: 98.6 dB, young females 106.2 dB). In a study of the vocal intensity in a group of elderly males (mean age = 77 years) and a control group of young males (Mean age = 30 years), who were asked to repeat the syllable /bæp/ at soft, comfortable, and loud intensities, Hodge et al. (2001) found SPL to be significantly greater in the younger control group. They proposed that the difference in vocal intensity between young and elderly voices was a "result of differences in lung pressure, peak airflow and open quotient" (p. 503). Similarly, in comparisons between young adult (Mean age = 26 years) and elderly groups (Mean age = 72 years), who were asked to repeat a series of /pæ/ at soft, comfortable, and loud intensities, Baker et al. (2001) also found that SPL was lower in older individuals than that in the younger group. It was speculated that aging-induced changes to the intrinsic muscles, as seen in lower laryngeal EMG measures, reduced laryngeal valving which resulted in inefficient modulation of the expiratory airflow and thus reduced vocal intensity. As described in Section 2.2.2.4 Intrinsic Laryngeal Muscles, EMG is a measure of the electrical activity produced by muscle activation in which the amplitude of the wave reflects the number of motor units activated, so the lower EMG measures reported here may explain the reduced laryngeal valving.

Jaw posture has also been reported to have an impact on vocal intensity. When asked to increase volume, people tend to increase the degree of jaw opening (Schulman, 1989; Dromey & Ramig, 1998; Huber & Chandrasekaran, 2006). Schulman (1989) recorded one female and three male Swedish speaking young adults (age range = 22-30 years) while they phonated 12 vowels with an initial high jaw position (for the vowel /i/) and found that normal articulatory movement increased with increases in intensity. Dromey & Ramig (1998) asked five females (Mean age = 32 years) and 5 men (Mean age = 31 years) to repeat a test sentence at normal intensity, at two loudness levels above normal intensity, and then at two levels below normal intensity. Measures of lower lip displacement showed that louder speech was associated with increases in lip displacement. In the same study, lower lip displacement became smaller when speech rate was increased. Huber & Chandrasekaran (2006), in a study of young normal female and male adults (Mean age = 22 years) also found that an increase in intensity resulted in greater jaw opening displacement.

Speech intensity is related to voice projection and voice projection may be related to the singing power ratio. Omori, Kacker, Carroll, Riley & Blaugrund (1996) defined the singing power ratio (SPR) as the ratio between the 'greatest harmonics peak between 2 and 4 kHz and the greatest harmonics peak between 0 and 2 kHz' (p. 228), which reflects the 'amplification or suppression in the vocal tract of the harmonics produced by the sound source', (Watts, Barnes-Burroughs, Estis & Blanton (2006), (p.82). Higher harmonics, particularly in the 2 to 4 kHz range have been reported to have an effect on vocal quality (Omori et al., (1996); Watts et al., (2006). A boost in the higher harmonics may come as a result of increases in sound intensity levels (Sunderberg (1973). Thorpe, Cala, Chapman and Davis (2001) found that greater voice projection was related to increases in SPR in a study of 5 professional classical singers (two tenors, two sopranos and one tenor) between the ages 26 and 59 with between 2 and 35 years of performance experience.

Voice projection increases with increases in SPR, and higher harmonics are boosted by increases in SPL. As discussed previously, because vocal intensity increases as jaw opening widens, changes in jaw posture might affect SPR.

2.5 Physiological Measures of the Aging Voice

This chapter provides a review of the literature related to the physiological measures of aging voice, including measures extracted from electroglottographic and aerodynamic signals.

2.5.1 Electroglottographic (EGG) Measures

Electroglottography is a non-invasive technique used to monitor changes to vocal fold contact during phonation. The EGG device passes high frequency, low current electrical signals through the vocal folds via electrodes placed on the external neck over the thyroid lamina at the level of the vocal folds. During the vibratory cycle when the vocal folds are in contact with each other, more current flows through them as it is conducted by the vocal fold tissues. When the vocal folds are separated, there is greater impedance of the electrical signal because electricity cannot be conducted through the air filling the open glottis. As the amount of impedance decreases, it is an indication that the vocal fold contact is increasing (Rothenberg & Mahshie, 1988). The variation in current during the different phases of the vocal fold vibratory cycle can therefore be measured, giving information about the relative time the vocal folds are open as well as the speed in which the vocal folds are opening and closing. Analysis of the relationship between the EGG measures and the physical movements of the vocal folds are expressed as ratios between the temporal measures of one particular phase of vocal fold movement with another phase and also between different phases of movement with the full glottal period. For example, open quotient (OQ) is defined as the ratio of the time the vocal folds are open (open phase) to the full glottal period. Speed quotient (SQ) is defined as the ratio of the opening phase to the closing phase (ratio of rise and fall time of the glottal flow).

In the few studies that examined aging and EGG measures, results have shown some evidence of an aging effect on vocal fold vibratory patterns (Higgins & Saxman, 1991; Winkler & Sendlmeier, 2005; Ma & Love, 2010). Higgins & Saxman (1991) defined the EGG duty cycle as the ratio between the open phase and the full glottal period measured from crossings at the 40% baseline. The 40% baseline (from which the crossing points of the waveform were derived) was calculated by subtracting 40% of the peak to peak amplitude from the maximum amplitude peak. A greater duty cycle suggests longer vocal fold open time and thus less vocal fold contact. They found that EGG duty cycle was greater in older males (Mean age = 75.3 years) than in younger males (Mean age = 24.1

years). In contrast, they found older females (Mean age = 74.6 years) had smaller duty cycles (greater vocal fold contact) than younger females (mean age = 26.6). The authors offered the explanation that these changes in duty cycle measures were the result of physiological aging which for males included vocal fold muscle atrophy, cartilage ossification, and vocal fold stiffening, and for postmenopausal women, vocal fold oedema. Similar results were reported by Ma & Love (2010), who found significantly smaller contact quotients for sustained vowels in older males (Mean age = 69.67 years) than in younger males (Mean age = 24.18 years). In the same study, a greater contact quotient for sustained vowels was found in older females (Mean age = 69.73 years) than younger females (Mean age = 25 years). Winkler & Sendlmeier (2005) also found OQ for males to increase with age for adults but found no significant differences in OQ between young (age range = 18-30 years) and old female speakers (age ranges = 59-82 years). Winkler and Sendlmeier (2005) attributed the increase in breathiness with age for adults in male adults to an increase of OQ, postulating that "increased breathiness may contribute to the listener's perception of increased age" (p. 213). In a study of 17 healthy males (age range 25-35, Mean age = 30 years) and 11 healthy males (age range 68-85, Mean age = 77 years) Hodge et al., (2001) found that in self monitored changes in intensity, OQ was significantly lower in the younger group than in the older group in each loudness condition.

In a study of 20 adult males (10 aged under 25 and 10 aged over 60), SQ was found to increase with age for adults (Murty, Carding, & Kelly, 1991). This increase was suggested to be evidence of a slower opening phase as a result of physiological aging A higher SQ, as a result of a slower opening phase, results in greater asymmetry within each cycle of the EGG waveforms. The symmetry of the EGG waveforms has been found to differ for different vocal qualities, with higher SQs being associated with perceptually tense or hyperfunctional voices (Childers & Lee, 1991) and in vocal fry (Chen, Robb, & Gilbert, 2002).

2.5.2 Aerodynamic Measures

Based on the myoelastic-aerodynmic theory of vocal fold vibration (Titze, 1994), the initiation and the sustaining of vocal fold vibration involves an intricate control of transglottal airflow and subglottal pressure. Pressure transducers can be used to track changes of the airflow and air pressure.

2.5.2.1 Mean Flow Rate (MFR)

Airflow can be measured as glottal volume velocity, which is the amount of airflow volume moving through the glottis at any given time. Airflow during phonation varies by the action of the opening and closing of the glottis during each glottal period. The pattern of airflow changes as it passes through the glottis, as illustrated in the contour of the glottal volume velocity waveform which starts with a gradual slope at first as the glottis is opening, rises to a peak when the vocal folds are at their fullest open position, and drops off during the closing phase of the vibratory cycle with a small delay due to the effects of inertia as air coming through the glottis meets the column of air already in the vocal tract (Scherer, 2006). The negative peak of the first derivative of the waveform (i.e., the peak at the lowest point plotted below baseline) corresponds to the greatest change in airflow volume and indicates the point of greatest excitation of the acoustic signal. This pattern of airflow (air movement) occurs during each glottal cycle.

Average airflow, mean flow rate (MFR), can be measured during sustained phonation of a vowel at a constant pitch level as an indication of respiratory power and the adequacy of glottal valving. As would be expected, when vocal folds do not adduct completely along their length during vibration, the effect is an increase in airflow leakage. The degree of incomplete glottal closure has been shown to be positively correlated with the airflow rate (Linville, 2002). Since vocal fold bowing is often found in the elderly, especially in the elderly men (as discussed in Section 2.2.7), airflow measures may be expected to increase with age for adults. Biever & Bless (1989) found greater variability in the measures of airflow rates for geriatric women than for younger women. In a study of 60 healthy men, Melcon et al. (1989) found that transglottal airflow was significantly higher in the oldest age group (75+) than in the other five age groups (25+, 35+, 45+, 55+, and 65+). Sapienza and Dutka (1996) investigated glottal airflow in 60 women in six age groups ranging from age 20 through to age 70s and found greater variability in peak airflow measures in the oldest (70+) age group than in the youngest (20+) age group. MFR tended to be higher in the elderly men and more variable for both elderly men and women.

2.5.2.2 Air Pressure

Subglottal air pressure is the aerodynamic force necessary to set the vocal folds into vibration and then sustain that vibration during phonation. Subglottal pressure can be obtained by use of an electromechanical transducer (i.e., strain gauge pressure transducer) using a direct or an indirect method. In a direct approach, a catheter is placed in the trachea either by inserting the catheter through the glottis (van den Berg, 1956) or through a tracheal puncture (Koike & Hirano, 1973). In an indirect approach, a catheter is placed on top of the tongue and the intraoral pressure (referred to as air pressure in this report) is used to represent subglottal pressure when the oral cavity and subglottal tract are equalized in pressure (Smitheran & Hixon, 1981). Although there is some evidence associating higher air pressure with a smaller vocal tract, more findings reveal no relationship between oral cavity size and air pressure, and air pressure is considered to be mainly affected by speech rate and vocal intensity (Brown & McGlone, 1969).

The effect of aging on air pressure has not been conclusively established due to conflicting findings in the literature. Ptacek et al. (1966a) found reduced measures of air pressure in geriatric men and women (Mean age = 76.9 years) when compared with young men (Mean age = 27.6 years) and women (Mean age = 23.5 years). Ptacek et al. (1966a) attributed this difference to aging-induced physical changes to the respiratory system, namely, a decrease in the power of the respiratory muscles. However, Melcon et al. (1989) failed to find any significant age effect on air pressure for males in comparisons of six age groups of men aged between 23 and 77 years. In a study of 20 young females and males (age range = 20-31 years) and 21 elderly females and males (age range = 69+), Higgins and Saxman (1991) found air pressure to increase significantly with age for adults for men but failed to find any significant age effect for women. In a study of 70 women (age range = 25-75), Hoit and Hixon (1992) did not find any significant age effect on air pressure. Using a series of /pæ/ repeated 5 to 7 times produced at three loudness levels (i.e., soft, comfortable, and loud), Baker et al. (2001) also failed to find any significant difference between a young age group of 2 men and 2 women (age range = 24-28), and an older group of one female and four males (age range = 68-79). As no significant aging effect was found in the majority of the studies and the direction of the significant aging effect reported was inconsistent, it is most likely that even if an effect of age-related physical change (e.g., vocal fold bowing) on air pressure existed, this effect might be masked by the high intersubject or intrasubject variability in the use of vocal behaviours developed to compensate for glottal incompetence.

2.5.2.3 Laryngeal Air Resistance (LAR)

Laryngeal airway resistance (LAR) is calculated as the ratio of transglottal (or translaryngeal) pressure to transglottal air flow (Smitheran & Hixon, 1981). Transglottal pressure can be estimated from the oral pressure measured when oral pressure is equalized with subglottal pressure such as in the case where the lips are closed and the glottis is open. Transglottal flow can be measured as the airway-opening flow during sustained phonation. Both measures can be derived from the production of a CV string, composed of a bilabial plosive (e.g., /p/) followed by a vowel (e.g., /a/). Air pressure is measured at the release of the plosive, and average airflow is measured from the vowel segment. The measure of LAR, representing glottal resistance to airflow, is used to describe laryngeal valving competency. The effect of the interaction between vocal fold adduction and transglottal flow pressure on LAR has been examined by Alipour, Scherer, and Finnegan (1997) using excised canine larynges. The LAR measure was found to increase either when (1) vocal fold adduction increased and subglottal pressure was held constant, or when (2) subglottal pressure increased, and vocal fold adduction was held constant.

In studies that examined the aging effect on LAR (Melcon et al., 1989; Hoit & Hixon, 1992; Holmes, Leeper, & Nicholson, 1994), aging effects, along with gender differences, were identified. In comparing six age groups (25+, 35+, 45+, 55+, 65+, and 75+), Melcon et al. (1989) found that LAR was significantly lower for men aged 75 than for men aged between 35 and 65. An examination of the two components of airway resistance, i.e., air pressure and airflow, revealed that whereas air pressure did not differ significantly among the six age groups, airway-opening flow measures on the other hand, were significantly higher for the 75-age group. The authors attributed the observed lower laryngeal airway resistance in the elderly voice to increased airway-opening flow measures as a result of aging-induced changes in laryngeal anatomy. Hoit & Hixon (1992) undertook a similarly designed study using female participants but failed to find any significant aging effect on LAR. The authors speculated that the aging effect on the laryngeal anatomy may be masked by the effects of some behavioural adjustments to voicing. Holmes et al. (1994), in a study of 10 healthy females and 10 healthy males (age range 55 to 75+), measured air pressure and airflow using the methodology described by Smitheran and Hixon (1981) and found that LAR was higher in the oldest (75+) female group than the other groups at all loudness levels. In addition, LAR was found to be greater in females than in males. These findings indicate that the expected lower LAR in the elderly voice due to lack of glottal competence is only evident in males.

The variability of LAR measures between individuals with dysphonia and normal contols has been investigated. In examining the air flow patterns in people with spasmodic dysphonia (SD), Finnegan, Luschei, Barkmeier, and Hoffman (1996) measured the coefficient of variation (COV) taken from the airflow of 10 SD subjects, two men (ages 38 and 64) and eight women (age range = 32-81 years), and 10 healthy control subjects, one male (aged 29) and nine females (age range = 29-64). High rates of COV measured in air flow were found in six of the 10 SD subjects, indicating increased variability of mean flow rate, “presumably reflecting increased instability of the phonatory system.” (p. 108). The authors pointed out that the airflow value taken from a single measurement from the midpoint of the airflow trace might not be representative of the full airflow rate and thus the LAR calculated from that measure may be problematic, particularly for disordered voices. This finding also indicated that LAR measures need to be interpreted cautiously with the variability of airflow taken into consideration.

2.6 Open Jaw Posture

The acoustic properties of voice are not only affected by the airflow and laryngeal movements but also by the shape and length of the vocal tract. In addition, the laryngeal position and vocal fold vibrating patterns may be affected by the structures in the vocal tract. A lowered jaw for example, has been shown to relieve muscular tension thereby promoting more relaxed voicing patterns (Boone & McFarlane, 1993; Colton & Casper, 1996) resulting in improved approximation of the vocal folds (Boone, 1977) and an increase in vocal fold adduction (Cookman & Verdolini, 1999). An open jaw posture has been used as a technique in voice therapy, e.g., the yawn-sigh approach and the Froeschel's chewing method, and is also a technique commonly used by professionally trained opera singers (Sundberg & Skoog, 1997).

2.6.1 Jaw Posture Effect on Phonation

The extent of jaw opening has been shown to affect phonatory measures, with increased jaw opening being associated with increased F0 (Austin, 2007; Sundberg, 2009), increased F1 frequency (Sundberg & Skoog, 1997), and decreased F2 frequency (Huber, Stathopoulos, Curione, Ash, & Johnson, 1999).

2.6.1.1 Jaw Opening and F0

Sundberg (2009) used magnetic resonance imaging (MRI) of the midsaggital vocal tract profile to measure the width of jaw and lip opening while a trained soprano performed melodic sequences on the vowels /a, e, i, u, o/. For all vowels, pitch increased as the jaw widened. Austin (2007) used a head mounted lip-jaw movement transducer system to measure jaw displacement on the superior-inferior plane as participants spoke and sang a carrier phrase embedded with the vowels /a, i, u/. The output from the transducer was synchronised with the microphone signal for analysis. Austin (2007) reported a significant increase in pitch with an increase in jaw opening in two groups of professional singers, including one group with less than four years of training and one group with greater than eight years of voice training. The number of years of singing experience was not shown to have an effect on the degree of jaw opening. In a study of 10 New Zealand English speaking males, a significant jaw effect on vowel F0 was found where the magnitude of jaw opening was inversely related to the natural F0 of individual vowels (Lim, Lin, & Bones, 2006). In Lim et al.'s (2006) study, jaw opening was recorded using a springloaded potentiometer positioned under the jaw, which was attached to a head mount to control head movement. Jaw movement output was synchronised with the acoustic and EGG signals for analysis.

2.6.1.2 Jaw Opening and Formant Frequencies

Formant one frequency has been shown to vary with the degree of jaw opening. In a detailed investigation of lip, tongue, jaw and larynx movements of one Swedish speaker by Lindblom & Sundberg (1971) using midsaggital x-rays of facial movements during phonation of sustained vowels, the frequency of F1 was found to be inversely related to jaw height, i.e., the lower the tongue, the higher F1. Sundberg and Skoog (1997) measured the degree of jaw widening using two transmitter coils, one attached to a plastic helmet and one attached with dental glue to an upper incisor, with a receiving coil attached to a lower incisor. The singers were asked to sing six vowels in ascending, two-octave scales; the lowest pitch recording of each singer was selected for analysis. They reported that jaw widening was used as an articulatory strategy by the 10 professionally trained singers to raise F1 when otherwise F0 would be higher than F1. The degree of jaw widening used to increase F1 was different for the different vowels. For example, although there was great variability among the singers, most singers started to widen their jaw as F0 approached F1 for the vowels /a/ and /ɑ/. A wider jaw opening increases pharyngeal constriction for these vowels, thereby increasing F1. In contrast, for vowels with a natural low F1, e.g., /u/ and /i/, whose F1 values are considered to be more sensitive to tongue constriction (Fant, 1960), the singers used tongue constriction rather than jaw opening to raise F1.

The relative frequencies of the first two formants, F1 and F2, have also been shown to provide acoustic information to the listener about the degree of jaw opening. Experienced listeners with more than 10 years of involvement in a professional opera company were able to identify the degree of jaw opening as a function of F1 and F2 frequencies (Erickson, 2004). This was part of a study whose main objective was to examine formant frequency and pitch perception on voice categories by investigating the relative effects of the lower formants (F1 and F2) and the higher formants (F3 and F4). In Erickson's (2004) study, listeners were presented with 14 pairs of stimuli with different specifications of the first four formant frequencies and were asked to rate the degree of jaw opening. When F1 and F2 were presented at high pitch and F3 and F4 at low pitch, the jaw was judged as being open. In the reverse combination, i.e., F1 and F2 in low pitch and F3 and F4 in high pitch, jaw posture was judged as being closed. These findings show that F1 and F2 frequency levels may be critical factors in judging of jaw position, with F1 and F2 at relatively higher frequencies were perceived as an indication of greater jaw opening.

2.6.2 Use of Open Jaw in Therapy

Varying the extent of jaw opening alters the size and contour of the oral cavity and would therefore be expected to affect the acoustic measures of voice. An "open mouth" (or "open jaw") approach, where people are asked to open their mouth while phonating, is commonly used in voice therapy for enhancing speech and voice production and relaxing the laryngeal musculature. Specifically, tense phonation is associated with elevation of the hyoid bone and, along with it, the larynx. In contrast, when the jaw is lowered, the hyoid bone is depressed, leaving the lowered larynx in a more relaxed position. A more relaxed larynx achieved through an open mouth posture would be expected to benefit phonatory competency.

An "open mouth" posture has been observed to promote more natural size and mass adjustments and better approximation of the vocal folds (Boone, 1977). Although this approach is often used either alone or in conjunction with other therapeutic techniques, it has not been subjected to rigorous experimental scrutiny. However, some evidence can be found in support of a positive effect of an open jaw posture on the voice. In a study of young healthy participants (age range = 18-42 years), Cookman & Verdolini (1999) found that increased jaw opening led to an increase in vocal fold adduction. In a study comparing lower lip and jaw displacement with measures of SPL in a group of 10 healthy adults (age range = 23-39), Dromig & Ramig (1998) found that SPL increased as the extent of lower lip and jaw displacement increased.

An open jaw posture is also employed in therapeutic strategies where it has been found useful for voice improvement. Firstly, the "yawn-sigh" technique, which involves jaw widening, has been shown to reduce laryngeal muscular tension by relaxing the vocal tract, opening up the pharynx, and lowering the larynx (Boone, 1977; Boone & McFarlane, 1993). As the larynx has been found to lower dramatically in a true vegetative yawn (Casper, Colton, Brewer, & Woo, 1989), it is most likely that jaw widening can lead to lowering of the laryngeal position and reduced vocal fold tension. Secondly, Froeschel's chewing method, which makes use of natural oral chewing movements to relax the mandibular musculature and to facilitate an open jaw posture, has been observed clinically to result in a more relaxed, healthier voice (Boone, 1977; Colton & Casper, 1996). Thirdly, it has been shown that jaw widening reduces laryngeal muscular tension (Boone, 1977, Boone & McFarlane, 1992) and that vocal exercises also focusing on reducing laryngeal area tension have produced positive phonatory outcomes in both singers and non-singers (Sabol, Lee, and Stemple, 1995). In their treatment efficacy study, Sabol, et al., (1995) compared 10 trained singers who underwent a vocal function exercise regime (i.e., adding sustained vowels and glides to their singing exercise practice) for a period of 4 weeks with a control group matched for age, gender, and years of vocal training. With acoustic, aerodynamic, and videostroboscopic analysis, singers in the training group were found to show increased glottal efficiency as compared with the matched controls. In the Lee Silverman Voice Training (LSVT) program for patients with Parkinson's disease, patients are encouraged to "talk loud". The LSVT technique has been shown to increase phonatory effort, reduce vocal fold bowing, and improve loudness (Smith et al., 1995). Ramig, Sapir, Countryman, Palas, O'Brien, Hoehn, and Thompson (2001), in a 2-year follow-up study of 21 patients with Parkinson's disease who underwent the LSVT program, have also demonstrated the efficacy and long-term maintenance effect of the treatment in increasing vocal intensity. An association between vocal intensity and jaw posture was discussed in Section 2.4.7. Sound Pressure Level (SPL). When people were asked to increase their intensity, they also tended to increase the degree of jaw opening (Schulman, 1989; Dromey & Ramig, 1998; Huber & Chandrasekaran, 2006). The usefulness of increasing intensity in voice improvement, as demonstrated in the LSVT program, and the relationship between changes in intensity and jaw opening, suggests the need to investigate the effect of jaw opening alone as a facilitative strategy for voice improvement.

In general, an open jaw posture when used as a therapeutic technique has been shown to improve vocal fold adduction, lower the larynx with a subsequent relaxation of the laryngeal musculature therefore reducing laryngeal tension, and is associated with increases in intensity for PD individuals.

2.7 Summary

The physical changes common in the normal aging process have been well described in the literature. These physical changes affect all parts of the vocal system, involving the respiratory system, the source of phonatory energy, the mechanics of the larynx, and the supraglottic tract. As the radiated voice reflects the combined input from these anatomic structures, an aging vocal system would be expected to produce an aging voice. Research has shown that listeners are able to identify speech characterized by reduced loudness and voice quality (hoarseness, tremor, roughness, and breathiness), imprecise consonants, and slower rates of speech as being elderly.

A variety of acoustic measures have been shown to reveal aging effects. Research has shown that as people age, F0 changes, with a tendency to lower in females and rise in males, and voice quality changes as jitter becoming more variable, shimmer significantly higher, and SNR significantly lower. The loci of formant frequencies also change as the dimensions of the vocal tract change with age for adults.

Changes in jaw posture, specifically an opening or lowering of the jaw, show an impact on the voice such as an increase in F1, SPL, and vocal fold adduction and a decrease in F2. These changes address some of the problems associated with the elderly voice. As a decrease in SPL is commonly observed in the elderly, lowering the jaw to increase SPL and better adduct the vocal folds could advantage elderly speakers. In addition, a shift in the F1, F2 vowel coordinates would also subsequently affect vowel space size. If this formant shift increases the distance between the corner vowels, thereby increasing vowel space size, there could be a change in speech intelligibility. A larger vowel space area has been associated with increased intelligibility as seen in a number of studies that compared the vowel space area of normal control adults with adults with dysarthria. With support from speech and/or voice therapy, vowel space area has also been shown to increase for fluency and muscle tension voice disorders after treatment.

A selection of instrumental measures, including EGG, airflow, air pressure, and acoustic measures have been found useful in the literature to track changes in the voicing mechanism. Although some aging effects on these measures have been identified in the literature, there are also conflicting findings which indicate the need for further investigation. Moreover, as there are indications of improved phonatory measures with an open jaw posture, an investigation into the effect of jaw opening on these measures in the normal healthy aging population is needed. The increase in the geriatric population and its concomitant increase in presbyphonia bring with it the need for documented evidence in support of facilitative strategies that may be applied in age-appropriate therapy for the elderly.

Chapter 3. RESEARCH OUTLINE

This chapter describes the aims and importance of the study, the research questions, and the proposed hypotheses.

3.1 Aims and Importance of the Study

Aging is often associated with some measure of physiological deterioration. Since norms for instrumental measures are less often derived from the aging population, applying conventional norms in the assessment of the geriatric voice may raise questions of suitability, or worse, produce erroneous results. The possibility of errors in the assessment of the elderly voice when comparisons are made against conventional norms should be considered. In one example, when standard dysarthria assessment criteria were used on a group of healthy elderly adults, 80% of this group were identified having mild dysarthria. Or, there may be the risk that pathological voices in the aging population being under-diagnosed due to a lower expectation for the aging voice, especially if there are no observable organic changes. In addition, studies of voicing behaviours in the geriatric population have produced varying, and sometimes conflicting results such as those found for %jitter, VOT and air pressure, highlighting the need for further research. An investigation of acoustic, EGG and aerodynamic behaviours in normal adults, grouped by age, may reveal patterns associated with the normal aging process.

Laryngeal behaviours are most likely to be affected by vocal tract configuration as well as phonatory context. The pattern of speech and voice changes in response to a facilitation strategy such as the use of an open jaw to change vocal tract configuration may provide information for the selection of an appropriate treatment approach. An open jaw posture is already a feature in some clinical strategies, e.g., the yawn-sigh approach, LSVT and Foreschel's chewing method, and has also been shown to relieve muscular tension and therefore promote a more relaxed voice. There has not been wide investigation in the use of an open jaw posture in the population of healthy aging adults as a facilitative strategy to improve speech and voice.

Based on these considerations, this study aims at using simultaneous instrumental measurements of acoustic, EGG, and aerodynamic recordings of the voices of non-hospitalized normally aging adults to identify patterns of aging, and to analyse the effect of an open jaw posture on this demographic group. With the increase in the number of people in the aging population and the projection that the number of people classified as geriatric will increase to about 25 percent of the population by the middle of the current century, there is a need for evidence-based management of geriatric voice. It is hoped that this study will yield information useful for the instrumental assessment of the elderly voice and provide information about the benefit of an open jaw posture as a therapeutic facilitative strategy in improving the geriatric voice.

3.2 Research Questions

The main research questions proposed in this study are:

1. Can an aging effect on the voice of normally aging adults be detected through the use of instrumental acoustic, EGG and aerodynamic measures?
2. What is the effect of an open jaw posture on the voicing behaviours of normally aging adults?

3. Can instrumental measures, which include acoustic, EGG, aerodynamic and jaw movement measures be used to assist in voice assessment, and to identify useful facilitative strategies in the management of the aging voice?

3.3 Hypotheses

Major hypotheses tested include:

1. Aging Effect: An aging effect on acoustic, EGG and aerodynamic measures will be more evident in the voices of older adults than the voices of middle age adults.
2. Jaw Posture Effects:
    a. Differences in acoustic, EGG, and aerodynamic measures will be found between vowels produced using a normal jaw posture and those produced using an open jaw posture.
    b. Vowels produced in an open jaw posture will demonstrate improved acoustic, EGG and aerodynamic measures compared to vowels produced in a normal jaw posture, which will result in improved measures of phonatory stability and speech intelligibility and clarity.

Chapter 4. METHODOLOGY

This chapter describes the research design of this study and includes details about participants, participants' tasks, instrumentation, measurement, data analysis, statistical analysis, and reliability.

The objectives of this study are to (1) provide instrumental voice analysis of the aging voice and to identify measures sensitive to voice assessment of the aging voice (2) to examine the effect of jaw posture on the aging voice, and (3) to examine if the use of instrumental measures can be applied to facilitative strategies for improving the aging voice, in particular, to identify if an open jaw posture can be used to improve the aging voice. Selected instrumental measures will be used on multiple voicing tasks such as vowel type, pitch level, phonetic context in sustained phonation and sentence tasks.

For this purpose, the design of the study required the participation of healthy females and males over the age 35; a full description of inclusion/exclusion criteria is presented in section 4.1 Participants. Recordings were made of simultaneous acoustic signals, EGG signals and facial tracking movements while the participants performed voicing tasks using the sustained isolated vowel /a/ in high pitch, low pitch, normal pitch, and /ma/ and /ha/ in normal pitch and repeating the research sentence 'We saw two cars.' To measure the impact of jaw posture, all tasks were performed using a normal and an open jaw posture at comfortable loudness levels. Mean Flow Rate and SPL were measured from simultaneous aerodynamic and EGG recording of the sustained isolated vowel /a/ produced in normal pitch and loudness levels in both a normal and open jaw posture. Air pressure and airflow were measured from five repetitions of /pa/ in one breath using normal pitch and loudness levels in a normal and open jaw posture. A detailed description of the research design is presented in the following sections.

4.1 Participants

A convenience sampling strategy was used to recruit healthy adults in four chronological age groups, “35-59 years” (35+), “60-69” (60+), “70-79” (70+), and “above 80” (80+), with at least five females and five males in each group. Five is the minimum sample size required for a factorial design study using analysis of variance (e.g., ANOVA) statistical tests. The age of the participants was defined as their full calendar age at the time of recording. For example, a participant with an age of 59;11 (i.e., 59 years and 11 months) at the time of recording was placed in the “35–59” age group. The purpose of this age grouping was to reflect a broad definition of how healthy adults age. Since there are reported patterns of physiological changes along the aging continuum, an age-based classification would allow for a general comparison between individuals at different stages in the aging process. Abitbol (2006) reported that atrophy of the vocal folds was not observed in patients before the age of 50, but there was 72% incidence of atrophy after age 70. After age 80, the incident rate of vocal fold atrophy increased to 81%, mostly with keratosis (tough fibrous proteins) present in the vocal muscle and ligament along with atrophy of the lamina propria. In the current study, the youngest group (35+) represents adults prior to the onset of physical aging that involve a change to vocal fold tissues. The oldest group (80+) represents healthy adults who are at an age where changes to the vocal fold tissues are shown in the literature to be more prevalent. The older participants were grouped into 10-year age brackets to investigate patterns of chronological aging. Since the younger group represented, as described above, healthy adults before aging affects are normally documented, they were placed into one age group.

In addition to the age grouping, gender was also taken into consideration. Research in the anatomy and physiology of normal aging has identified gender differences in the patterns of aging (Kahane, 1987; Pontes et al., 2005; Abitbol, 2006). One example of physiological aging differences between genders is the change in vocal fold mass. Vocal fold mass may increase for females as a result of menopausal hormone changes and decrease for males as a result of muscle atrophy. This gender difference may be related to the difference in vocal pitch, with the pitch tending to decrease for elderly women but increase for elderly men as discussed in the literature review. In view of these well-known gender-related differences in vocal aging, female and male data were analysed and reported separately.

Participants were recruited through personal contacts in the community and through advertisements posted on bulletin boards on the University of Canterbury campus and calling for interest in an article published in the newspaper of the local community group Age Concern, which supports issues for older people. The participant inclusion criteria consisted of non-hospitalised, mobile native English speakers over the age of 35 with no history of speech, voice, or severe hearing problems and no history of neurological disorders or surgery involving the head and neck area. Individuals who exhibited any observable sign of speech, voice, or severe hearing problems as assessed by a speech pathologist on the day of recording and those who were unable to follow directions were excluded. Two participants were excluded from the study. One, a 78 year old women presented with Alzheimer's Disease that had been diagnosed 10 years earlier. The diagnosis was unknown to the investigator prior to the recording session. The second participant excluded from the study was a 91 year old woman who was unable to follow the oral directions given by the investigator in the presentation of tasks. Examination of the task sequence presentation for the acoustic-EGG-facial tracking (see Appendix 7) and the aerodynamic protocols (see Appendix 4) shows that these tasks required the participants to switch the factors of pitch, task and jaw posture from one token to the next, which proved too difficult for the 91 year old woman.

To ensure all participants included in this study had normal speech motor function, a motor screening test was administered, which required them to follow a series of jaw, lip, and tongue movements as demonstrated by the investigator. The test items in the oral motor evaluation included facial, lip, and jaw movements such as moving the jaw from side to side, smiling with lips together and apart, and protruding, retracting, or lateralizing the tongue. Individuals who showed an inability to perform these tasks were excluded from the study.

A total of 85 participants were included in this study. All participants self-reported to have been living independently and actively interacting with family and friends within the community. Table 1 shows the age information for the female and male participants in the four age groups respectively.

Table 1. Number and age information for the participants as grouped by gender and age group.

Age Groups	Females			Males		
	n	Range	Mean (SD)	n	Range	Mean (SD)
35 – 59 (35+)	14	38 – 59	49.2 (6.3)	5	42 – 57	49.0 (5.7)
60 – 69 (60+)	17	61 – 69	65.6 (2.6)	7	61 – 69	66.1 (3.0)
70 – 79 (70+)	14	70 – 78	74.2 (2.4)	8	70 – 78	74.2 (2.4)
>= 80 (80+)	11	80 – 91	83.5 (3.1)	9	80 – 93	85.4 (4.2)

Twenty-seven participants (i.e., 31.8% of the total participants), including two females in the 35+ age group, four females and two males in the 60+ age group, nine females and four males in the 70+ age group, and three females and three males in the 80+ age group, reported some hearing loss. Only eight of these participants wore a hearing aid on the day of recording. The majority (23/27) of the participants who reported a hearing loss stated that the hearing loss became noticeable after the age of 60 years. Three participants reported a workplace noise induced hearing loss as an adult. One participant reported a war related hearing loss at age 22.

Participants who indicated a hearing loss on their interview form were asked for further details. When questioned about their reported hearing loss, none of the participants indicated that it was either problematic or interfered with daily living activities. All participants were living independently within the community; many were active in community groups which required good levels of inter-personal communication. An informal assessment of participants' hearing was performed by the investigator during the recording sessions. During the acoustic-EGG-facial tracking recordings the room was darkened (for facial tracking infrared video recording) and jaw posture instructions were written on an A4 paper held in front of the investigator's mouth, thus minimising visual cues. Additionally, during the aerodynamic recordings the investigator stood behind the participant while presenting instructions. All participants, except the two excluded from the study, were able to follow oral instructions without difficulty and in no way did their hearing loss interfere with their ability to complete the research tasks. The incidence of hearing loss in the demographic group from this study was comparable to statistics published by the National Institute on Deafness and Other Communication Disorders (NIDCD) (2010), an organisation of the U.S. Government National Institutes of Health. They reported that, 31.4% of people over the age of 65 have a hearing loss and 47% of people over age 75 have a hearing loss. In our study 38.9% of the participants over age 65 and 42.4% of the participants over age 75 identified a hearing loss.

Participants received a written description of the project (see Appendix 1). Each participant also completed a written questionnaire which asked for information about the participant's medical and voice related history as well as their history of smoking, alcohol, and caffeine consumption (see Appendix 2). The information on the interview form was discussed with each participant Prior to the experiment, each participant signed a participation consent form (see Appendix 3). Participants were compensated with a ten-dollar petrol voucher for their participation in the study. All forms and advertisements used in this study were approved by the Human Ethics Committee of the University of Canterbury, Christchurch, New Zealand; approval number HEC 2007/49.

4.2 Participants' Tasks

Participants were instructed to perform various voicing tasks at a comfortable loudness level using a "normal jaw" posture and an "open jaw" posture in three recording settings to allow for recordings of simultaneous airflow and EGG, simultaneous airflow, air pressure, and EGG, and simultaneous acoustic, EGG, and jaw movement tracking signals.

For the purposes of this study the term "normal jaw" posture is defined as the facial posture the participant would normally employ in conversation. The instruction to the participants was that they were to close their mouth before speaking and then to speak in their normal conversational manner. An "open jaw" posture is defined as speaking with the jaw lowered to a greater extent than in their 'normal jaw" posture. For the "open jaw" task, the instruction to the participants was that they were to start with their mouth closed and then 'open wide' while speaking. An A4 size sheet of paper with the written instruction "Open Wide" was held by the investigator during the open jaw tasks.

The recording protocol consisted of five trials for each experimental condition because that is the minimum number for each cell in the factorial design of the study.

The specific tasks for each recording setting are described as follows.

4.2.1 Simultaneous Airflow-EGG Recordings

For the simultaneous recordings of airflow and EGG signals, the participant was instructed to sustain the isolated vowel /a/ at a comfortable pitch and loudness level for approximately three seconds, in a "normal jaw" posture in five consecutive trials and then in an "open jaw" posture for an additional five consecutive trials (see Appendix 4.1). The protocol consisted of five consecutive trials for each experimental condition.

4.2.2 Simultaneous Airflow-Air Pressure-EGG Recordings

For the simultaneous recordings of airflow, air pressure, and EGG signals, participants were instructed to produce a sequence of five repetitions of /pa/ in one breath (i.e., /pa-pa-pa-pa-pa/) at normal pitch and loudness levels, using a "normal jaw" posture for five consecutive trials, and then an "open jaw" posture for an additional five consecutive trials (see Appendix 4.2).

4.2.3 Simultaneous Acoustic-EGG-Facial Tracking Recordings

For the simultaneous recordings of acoustic, EGG, and facial tracking signals, participants were asked to sustain the vowel /a/ for approximately three seconds in five different conditions, namely, (1) isolated vowel /a/ at a normal pitch, (2) isolated vowel /a/ at a low pitch, (3) isolated vowel /a/ at a high pitch, (4) /a/ initiated with /m/ at a normal pitch in one breath (i.e., /ma/), and (5) /a/ initiated with /h/ at a normal pitch in one breath (i.e., /ha/). The vowel /a/ was selected for this study because it can be produced in a normal jaw posture and in an open jaw posture without becoming distorted. This allows the speaker to phonate the vowel /a/ through a wide range of jaw opening positions. The sustained isolated vowel /a/ was phonated in normal, low and high pitch in order to investigate the effect of pitch on vowel phonation. As voice perturbation measures may vary by pitch, the inclusion of different pitch levels in the study will allow for an investation on how pitch and voice quality might be related in aging voice. The sustained vowel /a/ initiated with /m/ and with /h/ (i.e., /ma/ and /ha/) CV pairs were also selected to investigate the effect of a preceding consonant on vowel phonation. The /h/-initiated phonation has been commonly used in voice therapy for eliminating hard glottal attack and the /m/-initiated phonation has been used in the humming technique or resonant voice therapy to relax laryngeal musculature. Therefore, the inclusion of these tasks will allow for an investigation on the effect of these facilitating techniques on the aging voice.

Participants were asked to sustain /a/ in these five tasks using two different jaw postures, normal and open jaw. Each of the ten distinct testing conditions was repeated five times and was prompted in a pre-determined random order (see Appendix 5), resulting in 50 tokens (5 tasks X 2 jaw postures X 5 trials) in total. In addition, at regular intervals during the sustained vowel phonation tasks, participants were asked to repeat the four-word sentence "We saw two cars." The sentence was repeated in five consecutive trials using a normal jaw posture and then in five consecutive trials using an open jaw posture. This sequence was repeated a second time toward the end of this (i.e., acoustic-EGG-facial tracking) recording session, resulting in 20 trials of sentence production in total (Appendix 6). The test sentence "We saw two cars." contains the embedded vowels /i/, /ɔ/, /u/, and /a/. These corner vowels were selected because they represented the full extent of the vertical and horizontal positioning of the tongue in vowel production and thus allowed for an investigation on the effect of jaw opening on vowel space and the interaction between jaw opening and vowel height or forwardness on the acoustic representation of the vowels. Overall, the full testing sequence in the acoustic-EGG-facial tracking recording session consisted of 70 tokens, which included 50 sustained /a/ (isolated or initiated with a consonant) and 20 sentence productions (see Appendix 7).

4.3 Instrumentation and Instrumental Setup

The five components of the simultaneous recording system included the acoustic, airflow, air pressure, EGG, and facial tracking signal recording devices, which were setup in three configurations: (1) airflow-EGG, (2) airflow-air pressure-EGG, and (3) acoustic-EGG-facial tracking.

4.3.1 Simultaneous Airflow-EGG and Airflow-Air Pressure-EGG Recordings

The simultaneous airflow-EGG and airflow-air pressure-EGG recording systems included the Aerophone II (Kay Elemetrics, Lincoln Park, NJ USA) system, which consisted of a facemask and a catheter coupled with a transducer connected to the serial port of a computer and the electroglottographic device (Kay Elemetrics Model 6103, Lincoln Park, NJ, USA), which consisted of a connector box and two electrodes, each with a diameter of 3.5cm. The output of the EGG connector box was connected to an analogue-to-digital (A/D) converter as described in the following section.

The airflow transducer was calibrated at the start of each recording session using a 1-litre volume of forced air according to the manufacturer's (Kay Elemetrics Corp. Lincoln Park, NJ) instruction manual 'Instruction Manual Aerophone II Model 6800, May 1995.

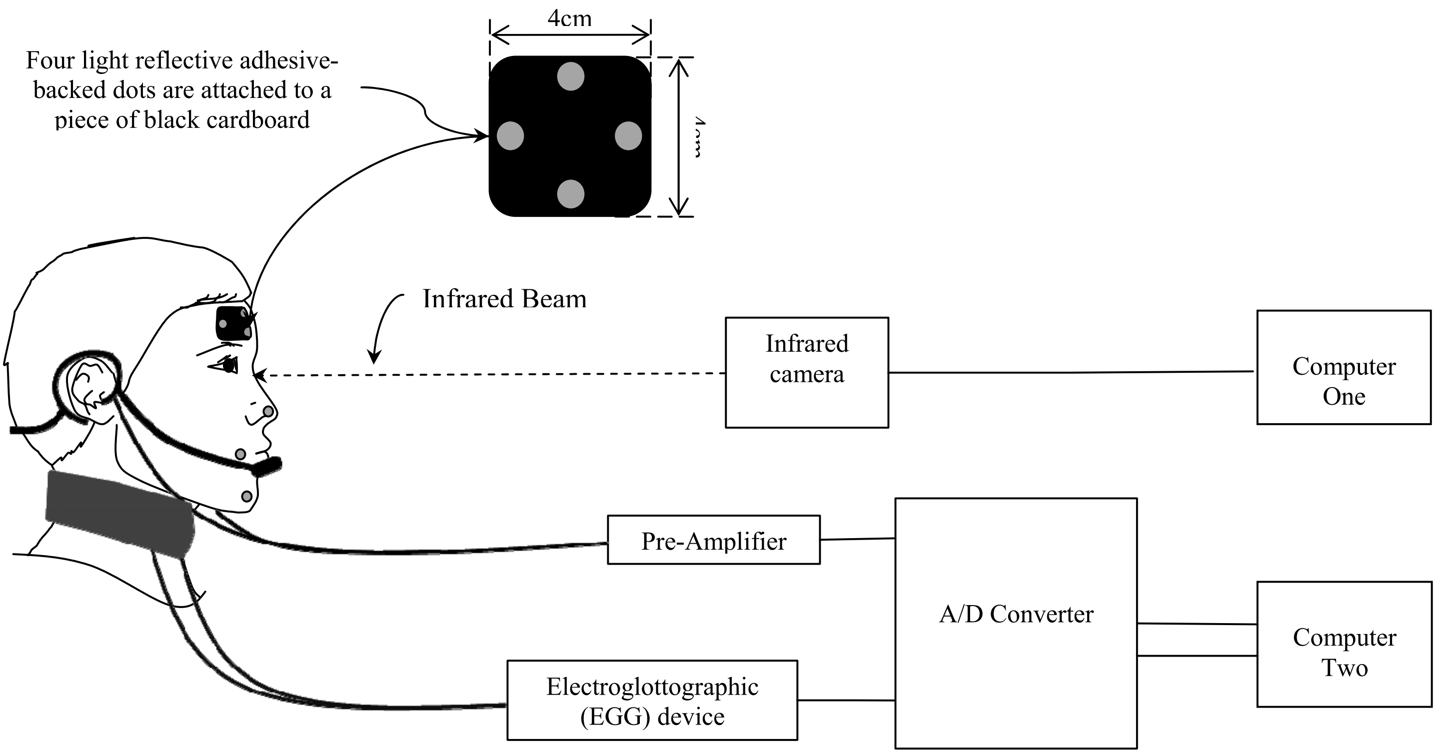
4.3.2 Simultaneous Acoustic-EGG-Facial Tracking Recordings

For simultaneous recordings of acoustic, EGG, and facial tracking signals, the acoustic system consisted of a headset microphone (AKG C420; Harman International, Vienna, Austria) and a mixer (Eurorack MX602A, Behringer, Willich, Germany) serving as a microphone preamplifier. Acoustic signals were recorded at a sampling rate of 44k. The outputs of the mixer and the EGG were connected to two separate channels of a 12-bit A/D converter (National Instrument DAQCard-AI-16E-4; Austin, TX) via a SCB-68 68-pin shielded connector box. The connector box contained a filter for each channel, with acoustic signals low-pass filtered at 20 kHz and EGG signals at 5 kHz. The A/D converter was housed in a laptop computer (Compaq 650 MHz Pentium 4; Compaq, Taipei, Taiwan) for direct digitization. A locally developed algorithm written in MATLAB 6.0 (The Mathworks, Inc., Natick, MA) was used to digitize acoustic and EGG signals. The video facial tracking recording system consisted of a mini-camera (1/4 CMOS PC Camera) equipped with two infrared LEDs (light-emitting diodes) placed on both sides of the lens. To ensure a stable video recording condition, the camera was fixed on a wooden beam supported atop a tripod. The output of the camera was connected to the USB port of a laptop (Compaq nx7400), which was equipped with a locally developed software written in C++ for data acquisition.

The microphone was calibrated with a calibration factor provided by the manufacturer (Bruel & Kjae "Integrating Precision Sound Level Meter," type 2230).

For acoustic recordings, participants were fitted with a headset microphone placed off axis 5 cm from the participant's lips. For EGG recordings, the two electrodes of the EGG device were secured on the participant's neck over the thyroid lamina held in place with a strap with Velcro fasteners. For jaw movement tracking recordings, four small circular silver reflector stickers, each with a diameter of 6 mm, were placed on the participant's face, with one at each corner of the lips, one in a middle position on the chin, and one on the tip of the nose. A piece of black-coloured paper (4 x 4 cm) with four round reflector stickers was secured to the middle of the forehead as a reference point. The infrared camera was placed in front of the participant at a distance of approximately 12 cm to capture the view of the eight circular stickers. The silver dots reflected the light emitted from the infrared light camera to allow for the tracing of the jaw movement. A schematic of the simultaneous acoustic-EGG-facial tracking recording system is shown in Figure **1.**

Figure 1. Schematic of the instrumentation used for the acoustic-EGG- facial tracking recordings.



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4.4 Procedures

Participants were seated comfortably in a quiet double-walled room designed to reduce background noise. Background noise was measured using a digital sound level meter (dick Smith Electronics, number Q1362). The background noise level was monitored and kept below 30 dB SPL. All recording sessions were scheduled during the day either in the morning or afternoon.

Recordings were obtained in one session comprised of three separate sections in the following order (1) airflow-EGG, (2) airflow-air pressure-EGG, and (3) acoustic-EGG-facial tracking. With the instrumentation in place, the participant was asked to perform the participant's tasks. Two investigators were present, with one giving instructions to the participant and the other controlling the recording system. In each session, recordings started with some trials for adjustment of the equipment and the tasks commenced without practice sessions. Water was provided and participants were encouraged to drink as needed during the recording session. Rest periods of approximately two to three minutes were provided while changes to equipment were made. Recordings were also paused at the participants' request when they wanted to drink water. All tasks were completed in one recording session which took approximately 45 minutes. All instructions were presented orally, with the addition of the printed instruction "Open Wide" held by the investigator for the open jaw tasks during the acoustic-EGG-facial tracking recording session. Since EGG signals were recorded in all of the three recording sessions, the EGG electrodes were placed on the participant's neck positioned over the thyroid lamina at the beginning of the recording session and remained there until the end of the recording session. Details for the procedure employed in each of the three recording sessions are described as follows.

4.4.1 Simultaneous Airflow-EGG Recordings

In the simultaneous airflow-EGG recording session, the participant was asked to hold a hand-held airflow facemask, which was attached to a pneumotachograph (see Section 4.3.1), to cover their nose and mouth and keep a tight seal between their face and the mask during phonation. The participant was prompted to perform the participant's task, which included, as previously described, sustaining an isolated vowel /a/ in a comfortable pitch and loudness level in two jaw postures. One investigator continuously checked to ensure a tight seal was maintained during phonation to prevent air from escaping. In cases where participants found it difficult to hold the mask securely in place, the investigator held the mask for them. The hand-held mask was removed from the face between individual trials. The EGG signals were saved as wave files, one for each trial. The airflow signals were recorded as Aerophone files, with all trials from each individual participant saved as a single file.

4.4.2 Simultaneous Airflow-Air Pressure-EGG Recordings

In the simultaneous airflow-air pressure-EGG recording session, the investigator inserted a plastic catheter of approximately 9 cm in length into the airflow mask, with the free end of the tube positioned on top of the participant's tongue. When the tube was put in place and the mask placed over the participant's nose and mouth with a tight seal, the participant was asked to perform the participant's task, which included, as previously described, a sequence of /pa/ production in one breath in two jaw postures. The tight seal between the mask and face was continuously monitored during the recording. For each trial, the EGG signals were saved as a wav file and the saved EGG files were organized in one folder for each participant. For each participant, the Aerophone recordings for all trials were saved as a single computer file, including subject information and the airflow, air pressure, and microphone signals obtained from the Aerophone system in three different channels.

4.4.3 Simultaneous Acoustic-EGG-Facial Tracking Recordings

In the simultaneous acoustic-EGG-facial tracking recording session, the room lights were turned off and the participant was seated against a black background to enhance the infrared light camera recordings. The participant was prompted to perform the participant's task in a pre-determined pseudo-random order. The participant was asked to close his/her mouth after each trial to ensure that each trial would start and end with the mouth in a neutral closed position. For each trial, the acoustic and EGG signals were digitized and saved as two separate wave files. The facial tracking signals and the video images were captured at a rate of 30 frames per second and saved as text files and image files respectively. The text files contained the time information and the change of the positions of the jaw and lips relative to the reference over time.

4.5 Measurements

Four different types of measurements were extracted from the acoustic, aerodynamic, EGG, and jaw movement tracking signals. Most of the experimental measures included in this study have been widely used in the investigation of voice and aging, including F0 (Hollien & Shipp, 1972; Biever & Bless, 1989), %jitter (Ramig & Ringel, 1983; Linville, 1987; Wilcox & Horii, 1980), %shimmer (Biever & Bless, 1989; Orlikoff, 1990), SNR (Xue & Deliyski, 2001; Ferrand, 2002), F1 and F2 (Endres et al., 1971; Xue & Hao, 2003), VOT (Sweeting & Baken, 1982; Decoster & Debruyne 2000), H1-H2 (Linville, 2002), and SPL (Ptacek et al., 1966a; Linville, 1996).

4.5.1 Acoustic Measures

Measures extracted from the acoustic signals included F0, perturbation measures, formant frequencies, vowel space area, H1-H2 amplitude difference, VOT, and vowel and sentence durations.

4.5.1.1 F0 and Perturbation Measures

As mentioned in Section 2.4.1, F0, expressed in Hertz, is the number of cycles of vocal fold opening and closing within one second. Perturbation measures, including jitter, shimmer, and SNR, are collectively used to describe the stability of the voice. As described in Section 2.4.2, jitter refers to the cycle-to-cycle variation in frequency and shimmer the cycle-to-cycle variation in amplitude for the time waveforms. The SNR measure is defined as the energy ratio between the periodic component of the signal and the noise component. Perturbation measures used in this study included percent jitter (%jitter), percent shimmer (%shimmer), and SNR. In this study, %jitter and %shimmer are expressed in percent and SNR is in dB (Milenkovic, 2001). The impact of age on F0 and perturbation measures has been widely investigated as discussed (see Sections 2.4.1 and 2.4.2).

4.5.1.2 Formant Frequencies and Vowel Space Area

Formants, which are concentrations of spectral energy shaped by the resonant characteristics of the vocal tract, have been shown to provide the key acoustic cues for vowel identification (Peterson & Barney, 1952; Hillenbrand et al., 1995). The frequency of F1 has been associated with tongue height, i.e., the lower the tongue, the higher the F1. The frequency of F2 is related to the “frontness” of the tongue, i.e., the more forward (anterior) the tongue bulge, the higher the F2. In addition, it has been theorized that the greater the pharyngeal constriction, the lower the F2. The resonant values of F1 and F2 have also been shown to be affected by vocal tract length. For example, it has been shown that all formants rise in frequency when the larynx raises and shortens the vocal tract (Sundberg & Nordstom, 1976).

With the F1 and F2 frequency values of the corner vowels plotted as two coordinates, a vowel space can be produced. As changes to the tongue and jaw position or the vocal tract length (via a rise or lowering of the larynx) may alter the F1 and F2 frequency values, the vowel space area can be used to reflect this change. Vowel space area has been found to be related to the perception of speech intelligibility (see Section 2.4.3.2). In particular, larger vowel space areas have been associated with better differentiation among vowels and thus higher speech intelligibility (Bond & Moore, 1994; Bradlow et al., 1996).

4.5.1.3 H1-H2 Amplitude Difference

The H1-H2 amplitude difference is the difference between the amplitude of the first harmonic, which is the F0, and H2 (see Section 2.4.3.3). This amplitude difference reflects the rate of amplitude decrease of the harmonics as a function of frequency and has been related to the perception of breathiness (Klatt & Klatt, 1990), with an increase in H1-H2 amplitude difference being perceived as breathier or thinner.

4.5.1.4 VOT

Voice onset time is the temporal measurement between the release of an unvoiced plosive and the start of the glottal pulse for the following vowel. The VOT has been shown to increase for females and decrease for males with age for adults (Torrre III & Barlow, 2009). In addition, VOT has been shown to exhibit greater variability with age for adults (Sweeting & Baken, 1982). Voice onset time is also influenced by rate of speech, i.e., as speaking rate slows, VOT increases (Miller et al., 1986; Miller & Volaitis, 1989; Kessinger & Blumstein, 1998). This is particularly relevant to elderly speech, which characteristically slows with age for adults (Smith et al., 1987; Brown et al., 1989; Linville et al., 1989).

4.5.1.5 Vowel and Sentence Durations

As mentioned previously, a slower rate of speech is one of the characteristics of elderly speech (Smith et al., 1987; Brown et al., 1989; Linville et al., 1989). In order to ascertain speech rate, the time duration of the four emdedded vowels, /i, ɔ, u, a/, as well as the full sentence duration, were measured from the sentence "We saw two cars." produced in both normal and open jaw postures.

4.5.2 EGG Measures

Two EGG measures were obtained, speed quotient (SQ) and open quotient (OQ). A 90% method was used for demarcation of the starting and ending of the opening and closing phases. In other words, the open phase is defined as the period starting and ending at the two points where the inverted EGG signal, which reflects the strength of impedance and thus the extent of the loss of glottal contact, reaches 90% of the full peak-to-valley voltage range in each cycle of the time waveforms.

4.5.2.1 SQ

Speed quotient is the time ratio of the opening phase to the closing phase. As the closing phase involves mainly the passive recoil of the vocal fold tissues, the closing time is normally faster than the opening time and relatively constant. The relative time length of the opening phase may be indicative of a change to the vocal fold stiffness or glottal competence.

4.5.2.2 OQ

Open quotient is the time ratio of the open phase to the cycle period and reflects the relative time the vocal folds remain open. Greater values in OQ indicate that the vocal folds are open for a longer period (as a fraction of the cycle) allowing for greater transglottal airflow which may be perceived as a breathier voice. Longer OQs have been found to increase with age for adults in males and are associated with an increase in breathiness (Winkler & Sendlmeier, 2005).

4.5.3 Aerophone Measures

The aerodynamic measures derived from the signals recorded with the Aerophone system included (1) the duration, SPL, and MFR of a selected steady mid-portion of a sustained vowel /a/, and (2) the air pressure, and airflow rate, and laryngeal resistance (air pressure divided by the airflow rate) derived from the /pa/ sequences.

4.5.3.1 SPL

An average SPL, measured in decibels, was extracted from a steady mid-portion of the sustained vowel /a/ obtained from the Aerophone system during the airflow-EGG recording session. Sound pressure level is dependent upon the physical integrity of the respiratory and laryngeal physiology and may therefore be sensitive to the aging effect as a consequence of the physiological changes that occur in the elderly. As discussed in Section 2.2.1, aging may lead to decreased respiratory volume, reduced elasticity (Morrison & Rammage, 1994), and calcification of the rib cartilages (Luchsinger & Arnold, 1967). The effects of aging on SPL was expected as SPL has been found to decrease with age for adults (Ptacek et al., 1966a; Hodge et al., 2001; Baker et al., 2001). As for jaw posture effect, increases in intensity have been associated with increases in jaw displacement in studies as previously discussed (see Section 2.4.7).

4.5.3.2 MFR

Measurements of the mean flow rate (in cc/sec) were taken from the same vowel segment used for measuring SPL as described in the previous section. The time duration of this selected steady segment was also recorded.

4.5.3.3 Air Pressure, Airflow, and LAR

Measures of subglottal pressure and airflow were derived from the air pressure and airflow signals simultaneously recorded during the airflow-air pressure-EGG recording session. The air pressure, measured in cmH_2O, was defined as the pressure of the peak in the pressure signal. This peak pressure is an oral pressure, which is equivalent to the subglottal pressure when the lips are closed and the vocal folds are open. Whereas airflow can be determined through direct measures by phonating through a facemask, air pressure can be measured noninvasively, albeit indirectly, when the glottis is open and the lips are closed, at which point the oral pressure equals the subglottal pressure (see Section 2.5.2.1). During production of /p/, the lips are closed and the vocal folds are opened thereby creating a single open tube from the trachea to the lips. Therefore, the peak intraoral pressure, upon its release, could be measured and taken as an equivalent of subglottal pressure. The average airflow of the steady vowel segment following the peak oral pressure was extracted from the simultaneously recorded airflow signals. The ratio of the peak pressure and the average airflow was derived as LAR, considered an estimate of the degree of laryngeal resistance.

4.5.4 Facial Tracking Measurements

Video facial tracking was used in this study to measure the magnitude of jaw displacement during phonation. Jaw position is known to affect a number of phonatory features including F1 (Linblom & Sundberg, 1971), pitch (Sundberg & Skoog, 1997; Austin, 2007), and vocal fold movement (Boon, 1997; Cookman & Verdolini, 1999). In order to ascertain the relationship between jaw opening and the acoustic variables used in this study, measures of the degree of jaw opening were needed. For this purpose, simultaneous recordings of jaw opening, acoustic, and EGG signals were obtained.

4.6 Data Analysis

Analysis was performed on the recorded signals using a selection of computer algorithms. The signal selection and analysis procedures are described as follows.

4.6.1 Acoustic Measures

The TF32 software (copyright: Paul Milenkovic, 2000, Madison, WI USA) was used for acoustic analysis. Acoustic analysis performed on the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) was analysed from a 500 ms steady segment of the vowel, starting 500 ms from the start of phonation (see Appendix 8). The length of the waveform for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) was at least two seconds in duration and thus allowed for an adequate 500 ms window for segment selection. For vowels embedded in the sentence, "We saw two cars", the vowel duration was much shorter so vowel segments shorter than 500 ms were selected. The time durations of the selected segments from the vowels embedded in sentences were between 50 and 200 ms. The vowel segments were cursor selected and exported as separate wav files.

4.6.1.1 F0, %jitter, %shimmer, and SNR

The acoustic measures F0, %jitter, %shimmer, and SNR were extracted from the full length of the vowel segment (500 ms for the sustained vowels and 50-200 ms for the embedded vowels) via the batch processing function in the TF32 "Jitter" module.

4.6.1.2 F1 and F2

The frequencies of F1 and F2 were extracted from a time slice in the same vowel segment used for deriving F0 and perturbation measures. The TF32 "Time Frequency" module was set with both the Preemphasis and the Linear Predictive Code (LPC) functions on the active mode. The time waveforms were displayed along side with the formant tracings highlighted in the spectrogram (see Appendix 8). The spectrum was visually checked and a point in time judged to be representative of the formant position within the vowel segment was selected for analysis.

4.6.1.3 Vowel Space Area

With the F1 and F2 of the four corner vowels (/i, ɔ, u, a/) plotted in two coordinates, the area enclosed by the quadrangle is defined as the vowel space area. In the current study, the first two formants were measured from each of the four vowels in the sentence "We saw two cars.", /i, ɔ, u, a/. The calculation of the quadrilateral vowel space area was achieved by first calculating the area of each of two triangles, one triangle defined by the three corner vowels /i/, /u/, and /a/, and the second triangle by the corner vowels /u/, /a/, and /ɔ/ using the formula: "vowel space area = ABS{[F1i*(F2a-F2u)+F1a*(F2u-F2i)+F1u*(F2i-F2a)]/2}" (Liu et al., 2005). For the second triangle, the formula was altered, replacing F1i and F2i with F1ɔ and F2ɔ. The vowel space quadrilateral area is the sum of the two individual triangle areas.

4.6.1.4 H1-H2 Amplitude Difference

The first two harmonic peaks, H1, and H2 of the acoustic data were measured in decibels. Analysis was performed using the TF32 Fast Fourier Transform (FFT) display with the Long Term Average Spectra (LTA) function enabled and Preemphasis disabled (see Appendix 9). The H1-H2 amplitude difference was calculated by subtracting the H2 amplitude from H1 amplitude.

4.6.1.5 VOT

In the current study, VOT was measured as the time period between the air burst from the unvoiced plosive /k/ production to the start of voicing for the vowel /a/ from the word “car” (VOT-/ka/) and from the unvoiced plosive /t/ to the start of voicing for the vowel /u/ in the word “two” (VOT-/tu/) in the test sentence “We saw two cars.” The data were analyzed by visually inspecting the spectrogram with formant frequency tracings generated through use of the TF32 Time Frequency setting with the LPC function (see Appendix 10). Voice onset time was measured in milliseconds.

4.6.1.6 Vowel and Sentence Durations

The spectrogram with formant frequency tracings were also used for measuring vowel and sentence durations. The length of each of the four embedded vowels, /i, ɔ, u, a/, and the full sentence length were measured using vertical cursor positioning to mark the beginning and ending points for each vowel and for the test sentence as a whole, giving duration times in milliseconds. One sentence produced with normal jaw and one sentence produced with open jaw was selected for each participant to yield measures of vowel length and sentence length.

4.6.2 EGG Measures

The EGG measures were calculated using a locally developed algorithm written in MATLAB 6.0 (The Mathworks). The EGG measures were derived from a 5,000 sample (approximately 113 ms) segment of the EGG signal corresponding to the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the four vowels embedded in the sentence “We saw two cars.” The selected segment was displayed as a differentiated EGG signal which was visually scrutinised to ensure that critical wave features would be included in the software analysis (see Appendices 11 and 12). The software calculated F0, SQ, and OQ from the selected EGG signal. Electroglottographic measurements were made using the vowel /a/ sustained in each of the five one-syllable tasks (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and for each of the four embedded vowels.

There were fewer EGG recordings than acoustic recordings because during the recording sessions some of the known problem conditions inherent in recording EGG waveforms were experienced. Some of the conditions identified by Colton & Conture (1990) that could prevent the high frequency, low current electrical signal from successfully passing from one electrode to the other through the vocal folds include participants whose necks are large or thick, those with a wide thyroid lamina angle (a wider angle increases the distance for the signal to pass), and those with smaller vocal folds. A fuller explanation of this issue is discussed in Section 8.2. In the end, EGG signals could not be recorded from 27 female and 2 male participants. The age information for the participants from whom EGG measures could be obtained is shown in Appendix 13.

4.6.3 Aerophone Measures

The Kay Voice Function Analyzer (F-J Electronics, Vedbaek, Denmark 2002) was used to extract measures from the airflow, air pressure, and microphone signals recorded using the Aerophone II system.

4.6.3.1 Sustained Vowel /a/

For signals recorded during the sustained vowel /a/ phonation, the airflow signals and the intensity traces extracted from the microphone signals were displayed on two time-aligned channels. The investigator cursor selected the steady mid-portion of the intensity trace and submitted the marked segment to an automatic processing function to derive measures of duration, mean flow rate, and SPL. For the sustained /a/ vowel phonation, a total of 850 segments (85 participants X 2 jaw postures X 5 trials) were analysed. The resulting values of the time duration, mean flow rate, and SPL of the selected segment were then entered into a spreadsheet.

4.6.3.2 /pa-pa-pa-pa-pa/

The airflow and air pressure signals simultaneously recorded during the /pa-pa-pa-pa-pa/ production were displayed on two time-aligned channels. The investigator cursor selected the middle section of the sequential /pa/ production to include the middle three pressure peaks. From the pressure signals, the pressure value of the peak with the median pressure value among the three middle peaks was recorded. From the flow signals, measures of the flow rate of the steady portion of the vowel following the three pressure peaks in the middle were also recorded. For the sustained sequential /pa/ production, a total of 2,550 segments (85 participants X 2 jaw postures X 5 trials X 3 middle repetitions) were analysed. The resulting values of the peak air pressure, average airflow rate, and LAR were then entered into a spreadsheet.

4.6.4 Jaw Displacement Measures

Analysis of the jaw movement signals obtained through the marker-based infrared light facial tracking system was performed using a locally developed algorithm written in MATLAB 6.0 and C++. The captured jaw and lip movement tracking signals were displayed on two time-aligned channels of a Matlab window. The investigator viewed the graphic representation of the jaw movement tracking signals, with time plotted on the x-axis and jaw displacement in millimetres on the y-axis. The facial movement data for two males with full beards could not be measured. The extent of jaw opening was measured from a neutral resting position at the start of phonation when the lips are closed (baseline measure) to the point of maximum jaw displacement, which could be identified as the highest peak in the facial tracking signal. The full video images saved as separate image files were also used to assist in verification of the integrity of the facial tracking signals.

4.7 Statistical Analysis

Data were analysed using the statistical analysis software SigmaStat version 2.03 (SPSS Inc.) and SPSS (version 17). Graphs were produced from the data using SigmaPlot version 8.0 (SPSS Inc.). Sample size for the age groups was calculated using the "Sample Size" function in SigmaStat. Values (group means and standard deviations and estimated group difference) used for determining sample size were based on the results of the pilot study conducted at the start of this research project. With all data collected based on the procedures as previously described, statistical tests were performed for the female and male data separately. Measures from the sustained phonation task and those from the embedded vowels obtained from the sentence task were also submitted to separate statistical analysis. Analysis was performed using three-way (sustained vowel /a/: 2 jaw postures X 4 age groups X 5 tasks; embedded vowels: 2 jaw postures X 4 age groups X 4 vowels) mixed model Analysis of Variances (ANOVAs). The Shapiro-Wilk test was used to test the normality of the data. Upon violation of the assumption of normal distribution, data was transformed before being submitted to further analysis. The Levene's test was used to test the assumption of homogeneity (i.e., equal variance). The Mauchly's test was used to test the assumption of sphericity. The Box's M test was used to test the assumption of equal covariance. Upon violation of the assumptions, the adjusted test statistics and p values were compared with the original test results for consideration in the interpretation of the results. The significance level was set at 0.05. Pairwise multiple comparisons using the Bonnferonni procedure with correction for multiple testings were conducted for the significant effect detected.

4.7.1 Acoustic Measures

The acoustic measures F0, %jitter, %shimmer, SNR, F1, F2, H1H2, and SPR obtained from the sustained phonation task and the embedded vowels were submitted to a series of three-way mixed model ANOVAs with one between-subject factor, age group (35+, 60+, 70+, and 80+), and two within-subject factors, jaw posture (normal vs. open) and either phonatory task (five levels: the isolated vowel /a/ in high pitch, low pitch, normal pitch and /ma/ and /ha/ in normal pitch) for the sustained vowels or vowel type (four levels: /i, ɔ, u, a/) for the embedded vowels.

A series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs were performed, for females and males separately, on the measures of vowel space area obtained from all participants and separately for different English-speaking accent groups. One of the inclusion criteria for this study was that English should be the participants' first language. From the community of English speakers, we recorded some participants who have lived their entire lives in New Zealand, as well as those who immigrated to New Zealand from other English speaking countries. The current research database consequently consisted of speakers whose vowel pronunciation might differ by nature of their different English accents. As F1 and F2 may vary by accent-related differences in the vocal tract configuration for vowel production, it is plausible that the calculated vowel space area would vary by accent. For this reason, in addition to performing statistics on the whole participant database for vowel space area, we also ran statistics using three subgroups from the database based on origin of accent, i.e., from New Zealand, British, and U.S.A. speakers (see Appendix 14). Statistics for vowel space area were not run for groups from other English speaking countries from the research database where there were too few participants, namely, South Africa (2 participants), Ireland (1 participant), and Scotland (1 participant).

4.7.2 Aerophone Measures

The Aerophone measures were averaged from the five trials in each task for each participant. The male and female data were analysed separately. A series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs were performed for each of the five aerophone measures SPL, MFR, air pressure, air flow rate, and LAR.

4.7.3 EGG Measures

Electroglottographic measures, SQ and OQ, obtained from each participant were separated by gender and submitted to a series of three-way mixed model ANOVAs with one between-subject factor, age group (35+, 60+, 70+, and 80+), and two within-subject factors, jaw posture (normal vs. open) and either task (five levels: the isolated vowel /a/ in high pitch, low pitch, normal pitch and /ma/ and /ha/ in normal pitch) for vowels sustained in a one-syllable task or vowel type (four levels: /i, ɔ, u, a/) for vowels embedded in a sentence.

4.8 Reliability

To assess measure-remeasure reliability, 20% of the total acoustic and EGG recordings were re-measured following the same measurement methodology used for the initial measurements. Acoustic and EGG recordings were randomly selected for re-measurement. The random selection of recordings was performed using a computer based random number generator. The internet site www.random.org uses tests that originate from several sources, but the majority they use are recommended by the US National Institute of Standards and Technology (NIST), Gaithersburg, MD. NIST is a United States Government agency that sets standards for scientific measurements. A series of Pearson Product Moment correlation procedures was performed on the two sets of corresponding measures. The Pearson Product Correlation was performed on all trials for each of the participants selected for re-measure. The reported correlation coefficient reflects the within-subject variability. The reliability ranged from moderately to relatively high.

4.8.1 Acoustic Measures

A group of 17 participants (20% of participants) were randomly selected for re-measurement of all test conditions for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). Another group of 17 participants were randomly selected for re-measurement of all 80 vowels embedded in 20 productions of the sentence "We saw two cars." Results from a series of Pearson Product Moment correlation procedures performed to assess the measure/re-measure reliability of F0, %jitter, %shimmer, SNR, F1, and F2 are summarized in Table 2. As shown in Table 2, the measure-remeasure reliability for measures from both sustained and embedded vowels were generally high. The correlation coefficients were slightly lower for the F1 and F2 measures obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and for the %jitter and %shimmer measures obtained from the embedded vowels (/i, ɔ, u, a /).

Table 2. Measure/re-measure correlation coefficients for the acoustic measures (F0, %jitter, %shimmer, SNR, F1, and F2) obtained from the sustained and embedded vowels.

Acoustic Measure	Sustained Vowels	Embedded Vowels
F0	0.96	0.89
%jitter	0.88	0.68
%shimmer	0.85	0.83
SNR	0.92	0.95
F1	0.72	0.97
F2	0.66	0.91

The less consistent measurement outcomes for the %jitter measures obtained from the embedded vowels may be due to the greater pitch variation in the sentence task as compared with the sustained phonation task. The less consistent measurement outcomes for the formant frequency measures obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) may be due to the longer length of vowel available for selection in this task. In the selection of the vowel segment from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), a 500 ms segment was selected from a waveform of 2,000 ms to 3,000 ms in duration. Although both the measure and re-measure segments were extracted from the same steady portion of the waveform, it is less likely that the exact same 500 ms segment would be selected. On the other hand, because the original waveforms for the embedded vowel /a/ were shorter, in most cases similar vowel segments were extracted for the initial measurement and the re-measurement of the data and thus a higher measure-remeasure reliability for the F1 and F2 measures.

4.8.2 Segment Length

Measures of vowel and sentence durations were subjected separately to a re-measure of 17 randomly selected participants (20% of participants) using normal and open jaw posture. A Pearson Correlation was performed on the first and second measuring sets of the durations of the four vowels /i/, /ɔ/, /u/, and /a/ and the test sentence in milliseconds. Reliability was found to be relatively high with a correlation coefficient of 0.99.

4.8.3 EGG Measures

Twenty percent of the participants (12 participants) were randomly selected for re-measurement of the EGG signals. A total of 50 EGG signal files recoded during the acoustic-EGG-facial tracking session were reprocessed for each selected participant. As shown in Table 3, results from a series of Pearson correlation procedures revealed moderately high measure-remeasure reliability for the EGG measures.

Table 3. Measure-remeasure correlation coefficients for the EGG measures (F0, SQ, and OQ) obtained from isolated vowel /a/ in normal pitch.

EGG Measures	Correlation
F0	0.94
SQ	0.73
OQ	0.73

4.8.4 Aerophone Measures

Thirty-seven percent (317/850) of the air pressure signals were randomly selected for re-measurement. Results from the Pearson correlation procedure performed on the two sets of measures also revealed a relatively high measure/re-measure reliability ($r = 0.93$).

Chapter 5. RESULTS

This chapter presents results from the statistical analysis of the acoustic, EGG, aerodynamic, and facial tracking measures. Based on the isolated vowel /a/ sustained at normal, high, and low pitch, and initiated at normal pitch with a consonant /m/ or /h/, statistical results were reported for eight acoustic measures, including F0, %jitter, %shimmer, SNR, F1, F2, H1H2, and SPR, and two EGG measures, SQ and OQ. Based on the vowels /i, u, a, ɔ/ embedded in the sentence “We saw two cars”, statistical results were reported for seven acoustic measures, including F0, %jitter, %shimmer, SNR, F1, F2, and vowel space area, and two EGG measures, SQ and OQ. In addition, statistical tests on the VOT and sentence and vowel duration are also reported based on the acoustic measures obtained from the sentence “We saw two cars”. Results for the aerophone recordings are reported for measures of SPL and MFR from the isolated vowel /a/ sustained at normal pitch and measures of air pressure and airflow rate from the /pa/ repeated in a sequence at normal pitch.

5.1 Acoustic Measures

Results from a series of three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs performed on the original or transformed acoustic measures (F0, %jitter, %shimmer, SNR, F1, F2, and H1H2) for the sustained vowel /a/ and three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs on these measures for embedded vowels /i, u, a, ɔ/ are presented for females and males separately in Tables 4 to 15 and 17.

In addition to results from the inferential statistics, means and standard deviations of the acoustic measures (F0, %jitter, %shimmer, SNR, F1, F2, H1H2, and SPL) for the isolated vowel /a/ sustained at normal pitch are organized by age group and jaw posture are presented in Appendices 15 and 16 for females and males respectively. Based on the vowel /a/ produced at normal pitch, means and standard deviations of acoustic measures and aerodynamic measures (MFR and air pressure) organized by gender and age group are presented in Appendix 17 with normal and jaw combined, and those organized by gender and jaw posture are presented in Appendix 18 with all age groups combined. Means and standard deviations of the acoustic measures (F0, %jitter, %shimmer, SNR, F1, and F2) for the embedded vowel /a/ are organized by age group and jaw posture and presented in Appendices 19 and 20 for females and males respectively.

5.1.1 F0

This section details the statistical results of the F0 measures obtained from the sustained vowel /a/ and from the embedded vowels /i, u, a, ɔ/.

5.1.1.1 Vowel /a/ Sustained In a One-Syllable Task

The F0 values obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) were transformed into log(F0) to fulfil the assumption of normality before being submitted to a three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVA. As shown in Table 4, the ANOVA results revealed significant posture and task effects for both females and males. In addition, a significant posture by task interaction effect was found for females and significant age group effect and age group by posture interaction effect were found for males.

Table 4. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on F0[ξ] for sustained vowel /a/ in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	2.290	0.089	0.12	3, 25	4.297	0.014*	0.34
Posture	1, 52	93.262	< 0.001**	0.64	1, 25	43.811	< 0.001**	0.64
Task	4, 208	230.300	< 0.001**	0.82	4, 100	211.216	< 0.001**	0.89
Age X Posture	3, 52	1.719	0.175	0.09	3, 25	3.845	0.022*	0.32
Age X Task	12, 208	0.913	0.535	0.05	12, 100	0.936	0.514	0.10
Posture X Task	4, 208	6.856	< 0.001**	0.12	4, 100	0.614	0.654	0.02
Age X Posture X Task	12, 208	1.321	0.208	0.07	12, 100	0.698	0.750	0.08

[ξ]The F0 values were transformed into log(F0) before being submitted to ANOVA tests. The female transformed data passed the Box's M test of equal covariance. Both female and male transformed data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

For females, follow-up pairwise multiple comparisons revealed that across all of the five tasks, open jaw posture was associated with a significantly higher mean transformed F0 value than normal jaw posture. Regardless of jaw posture, low-pitch condition was associated with the lowest transformed F0 value and high-pitch condition with the highest transformed F0 value as expected (see Figure 2). As shown in Figure 1, with normal jaw posture, the /m/-initiated condition was not significantly different from the normal-pitch condition but the /h/-initiated condition was significantly higher than both normal-pitch and /m/-initiated conditions. With open jaw posture, the normal-pitch, /m/-initiated, and /h/-initiated conditions were not significantly different from one another on the transformed F0 values.

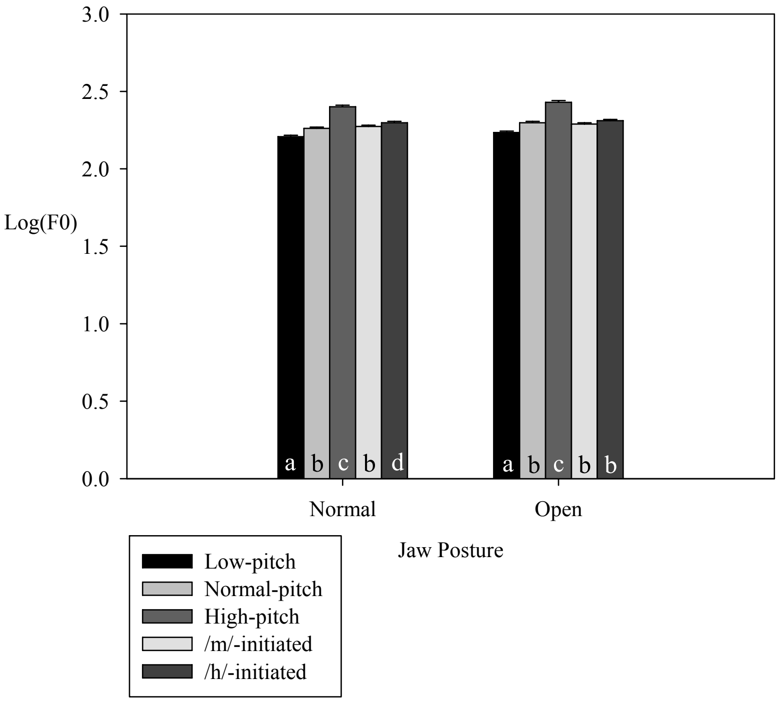


Figure 2. Means and standard errors of the transformed F0 measures for sustained vowel /a/ in females across postures (normal vs. open) and tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups combined. Significantly different means are marked with different letters.

Although the three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVA conducted on the transformed F0 values in females failed to reveal a significant age group effect, a planned post-hoc one-way ANOVA on Ranks conducted on the F0 measures in females with all tasks and postures combined revealed a significant age group effect ($H = 33.062$, $df = 3$, $p < 0.001$) and pairwise multiple comparisons using Dunn's method showed that F0 was significantly higher in the 35+ age group than in the elderly groups except for the 70+ age group (see Figure 3). It is noteworthy that the average F0 for the vowel /a/ sustained at normal pitch (with normal and open jaw combined) in females decreased from a mean of 202 Hz in the 35+ age group to a mean of 177 Hz in the 80+ age group (Appendix 17).

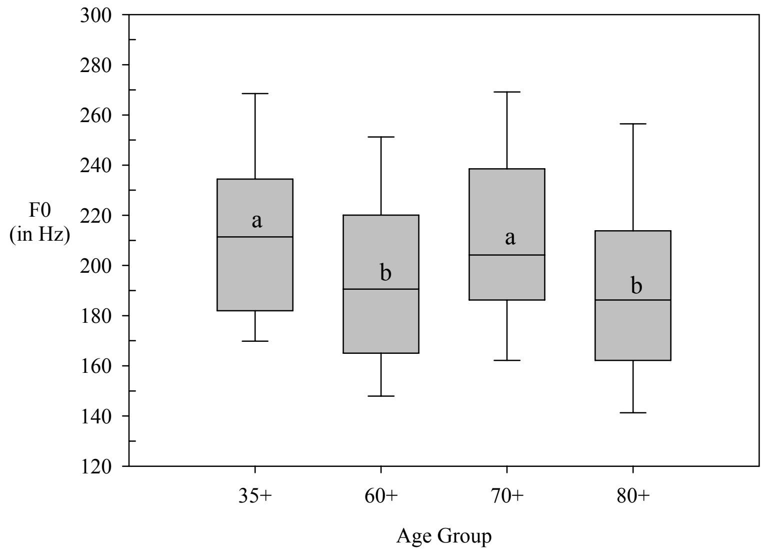


Figure 3. Box plot of the F0 measures across age groups for sustained vowel /a/ in females, with the median shown as the line within the box, the 25th and 75th percentiles as the lower and upper boundaries of the box, and the 10th and 90th percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters.

For males, follow-up pairwise multiple comparisons for the task effect revealed that low-pitch condition was associated with the lowest F0 measure and high-pitch condition with the highest F0 measure as expected. Like the finding for the open jaw posture condition in females, the normal-pitch, /m/-initiated, and /h/-initiated conditions for males, regardless of jaw posture, were not significantly different from one another on the transformed F0 values (see Figure 4).

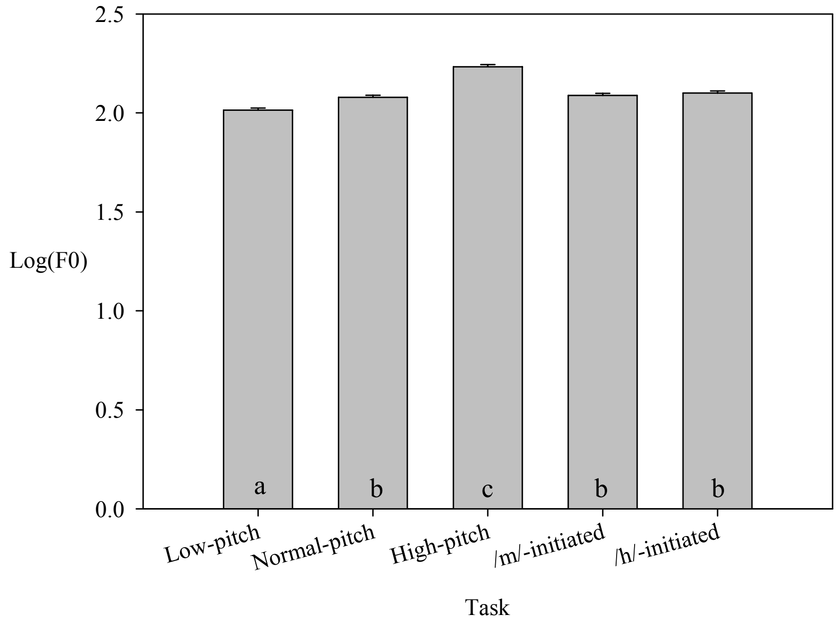


Figure 4. Means and standard errors of the transformed F0 measures for sustained vowel /a/ in males across tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups and postures combined. Significantly different means are marked with different letters.

As for the age group by posture interaction effect on the transformed F0 values of the sustained vowel /a/ in males, the mean transformed F0 values were consistently higher in an open jaw posture condition than in a normal jaw posture condition across all age groups, but this posture difference only reached a statistically significant level for the 80+ age group (see Figure 5). In addition, for the normal jaw posture in males, the two lower age groups (35+ and 60+) exhibited significantly lower F0 measures than the two older age groups (70+ and 80+). Figure 5 also shows that, for the open jaw posture in males, the 35+ age group had a significantly lower mean F0 measure than the other three older age groups (60+, 70+, and 80+) and the 60+ age group had a significantly lower mean F0 measure than the oldest age group (80+). It is evident that the F0 measures in males showed an aging pattern opposite to those in females, with F0 in males increased from a mean of 104 Hz in the 35+ age group to a mean of 134 Hz in the oldest 80+ age group (Appendix 17).

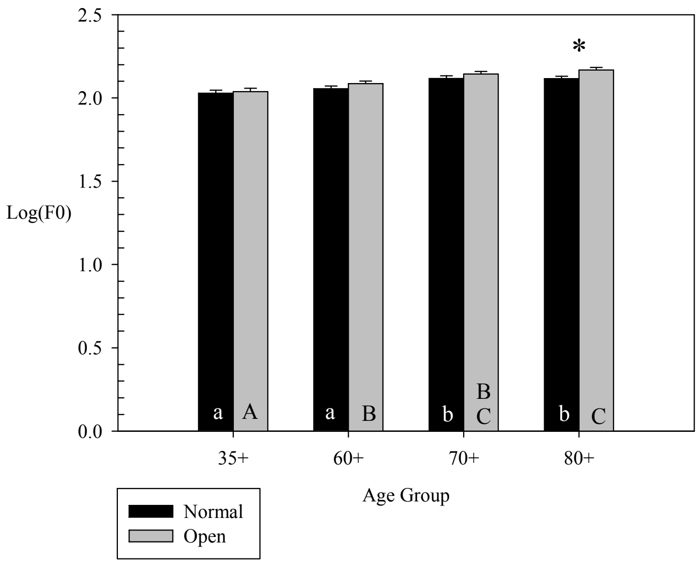


Figure 5. Means and standard errors of the transformed F0 measures for sustained vowel /a/ in males across age groups (35+, 60+, 70+, and 80+) and postures (normal vs. open) with all tasks combined. Significantly different means between age groups are marked with different letters and those between jaw postures are marked with an asterisk ("*").

5.1.1.2 Embedded Vowels

As shown in Table 5, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the F0 measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects and age group by vowel and age group by posture by vowel interaction effects for females and significant age group, posture, and vowel effects and age group by vowel interaction effect for males.

For females, the finding in the embedded vowels that the open jaw posture, with all age groups and vowels combined, was associated with a significantly higher mean F0 (196 Hz) than the normal jaw posture (187 Hz) agrees with the finding in the sustained vowel /a/ as previously described. Figure 6 illustrates the age group by vowel interaction effect, showing that the vowel /i/, for both normal and open jaw postures, had a significantly higher mean F0 than /u/ and /a/ across all age groups but the low vowel /ɔ/ had a significantly higher mean F0 than /a/ only for the youngest age group (35+).

Table 5. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on F0[ξ] for embedded vowels /i, u, a, ɔ/ in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	0.951	0.423	0.05	3, 25	3.907	0.020*	0.32
Posture	1, 52	16.115	< 0.001**	0.24	1, 25	13.289	< 0.001**	0.35
Vowel	3, 156	92.623	< 0.001**	0.64	3, 75	20.331	< 0.001**	0.45
Age X Posture	3, 52	1.400	0.253	0.08	3, 25	1.266	0.308	0.13
Age X Vowel	9, 156	2.801	0.004**	0.14	9, 75	2.097	0.040*	0.20
Posture X Vowel	3, 156	0.535	0.659	0.01	3, 75	0.722	0.542	0.03
Age X Posture X Vowel	9, 156	2.798	0.005*	0.14	9, 75	1.333	0.235	0.14

[ξ]The female raw data failed the Box's M test of equal covariance. The female raw data passed but he male raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

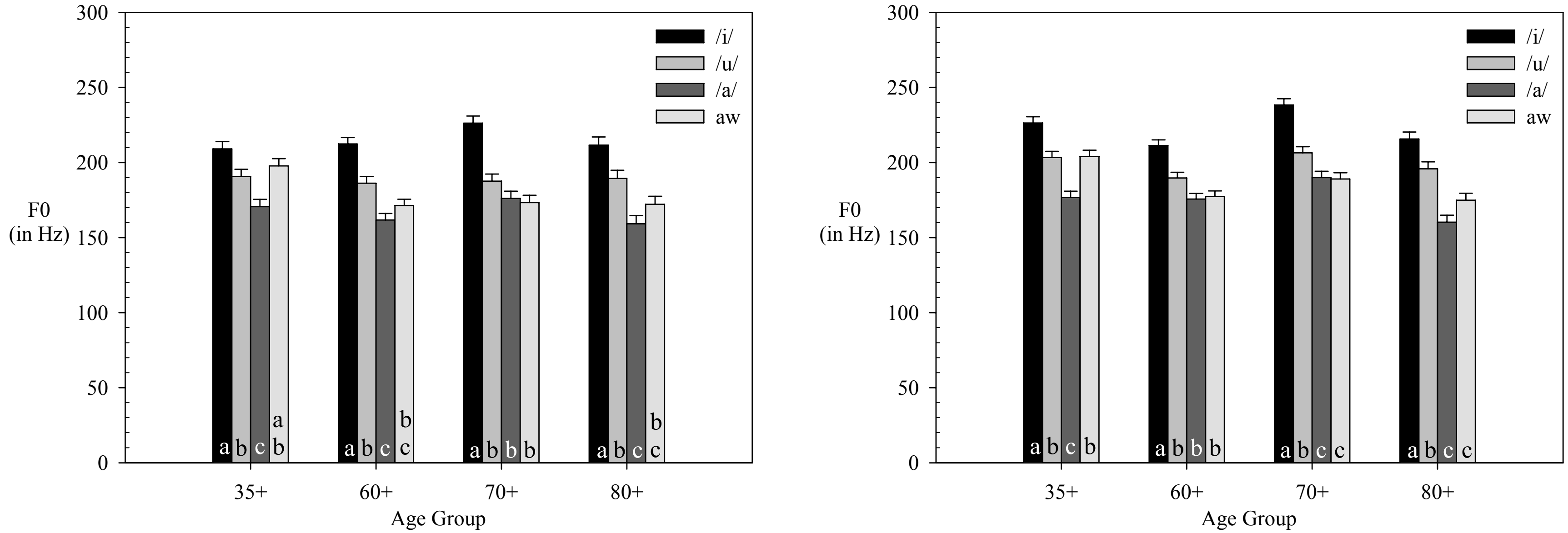


Figure 6. Means and standard errors of the F0 measures for embedded vowels in females across age groups (35+, 60+, 70+, and 80+) and vowels (/i, u, a, ɔ/; Note: the vowel /ɔ/ is written as "aw" in the graph) for normal (left graph) and open jaw postures (right graph). Significantly different means are marked with different letters.

For the embedded vowels in males, open jaw poture yielded a significantly higher mean F0 (133 Hz) than normal jaw posture (122 Hz) with all age groups and vowels combined. As for the age group by vowel interaction effect, Figure 7 shows that F0 generally increases with age for adults, especially with the older age groups (70+ and 80+) exhibiting significantly higher average F0 than the two younger groups (35+ and 60+) for the vowel /i/.

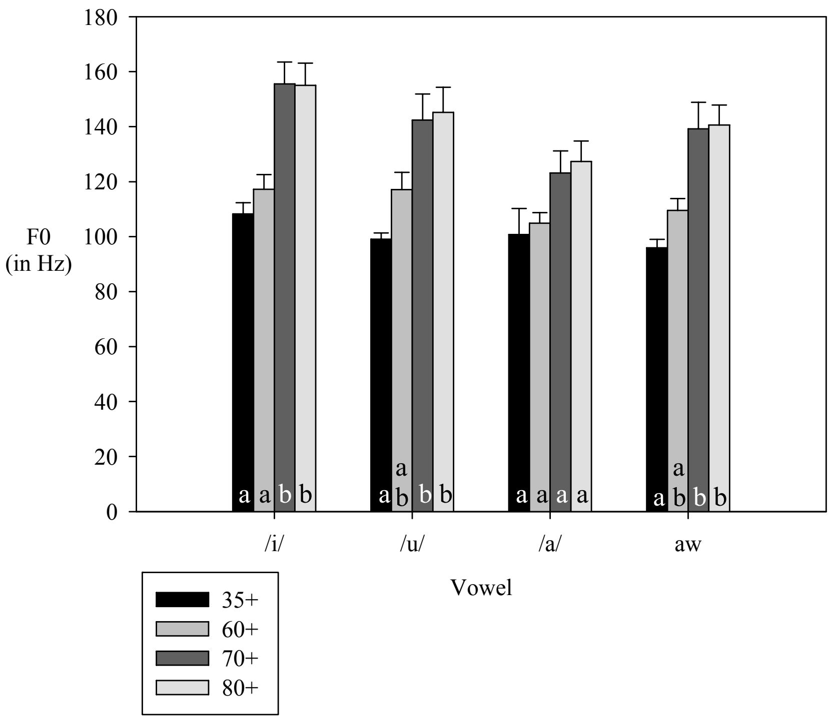


Figure 7. Means and standard errors of the F0 measures for embedded vowels in males across age groups (35+, 60+, 70+, and 80+) and vowels (/i, u, a, ɔ/; Note: the vowel /ɔ/ is written as "aw" in the graph). Significantly different means are marked with different letters.

In summary, as age increased, F0 measures generally decreased for females and increased for males based on findings from the sustained vowel /a/ and the four embedded vowels. For both females and males, the open jaw posture resulted in a higher F0 than the normal jaw posture regardless of age group, task, and vowel, although the jaw posture difference on F0 for the sustained vowel /a/ in males reached a statistically significant level only for the oldest group (80+). As for the task effect, the sustained vowel /a/ for both females and males showed similar F0 measures for normal-pitch, /m/-initiated, and /h/-initiated conditions and significantly lower F0 in the low-pitch condition and significantly higher F0 in the high-pitch condition as expected. For both females and males, /i/ had the highest F0 and /a/ had the lowest F0 but the degree of some vowel differences on F0 varied by age groups in both females and males and by jaw posture in females.

5.1.2 Phonatory Stability

This section includes statistical results for the phonatory stability measures, including %jitter, %shimmer, and SNR.

5.1.2.1 Percent Jitter

Statistical results are reported for %jitter derived from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the embedded vowels /i, ɔ, u, a/ separately.

5.1.2.1.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Table 6, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the transformed %jitter values for the sustained vowel

/a/ revealed significant age group, posture, task effects and posture by task and age group by posture interaction effects for females and significant posture and task effects for males.

For females, a pattern of %jitter increasing steadily with age for adults could be observed and results from pairwise multiple comparisons showed that the mean transformed %jitter was significantly higher in the 80+ age group as compared with all the other age groups regardless of jaw posture (see Figure 8). A pattern of %jitter increasing with age for adults could also be observed from the increase of mean %jitter from 0.386 in the youngest age group (i.e., 35+) to 0.854 in the oldest age group (80+) for the isolated vowel /a/ sustained by females at normal pitch (see Appendix 17). This finding agrees with the finding in a study of healthy females by Ramig & Ringel (1983), which showed an increase of mean %jitter from 0.424 in young females (ages 25-35) to 0.596 (ages 65-75) and 0.54 (ages 70-79) in two older female groups. In Ramig & Ringel (1983), the %jitter result is similar to that in the current study especially when the age groups are matched. For example, with the 80+ age group excluded from the comparison, it can be observed that %jitter increased to 0.476 in the 70+ age group (see Appendix 17).

As for the age group by task interaction effect, the open jaw posture generally resulted in a lower %jitter than the normal jaw posture across all age groups although the posture difference on %jitter was statistically significant only for the 60+ age group (see Figure 8). For the task by posture interaction effect found in females, pairwise multiple comparisons revealed that the transformed %jitter of the sustained /a/ in the low-pitch condition was significantly higher than in the high-pitch and /h/-initiated conditions regardless of jaw posture but high-pitch condition was significantly lower than the /h/-initiated condition only for the normal jaw posture (see Figure 9).

Table 6. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on %jitter[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	5.730	0.002*	0.25	3, 25	0.921	0.445	0.10
Posture	1, 52	39.948	< 0.001**	0.43	1, 25	11.811	0.002**	0.32
Task	4, 208	27.423	< 0.001**	0.35	4, 100	17.706	< 0.001**	0.42
Age X Posture	3, 52	3.074	0.036*	0.15	3, 25	0.346	0.792	0.04
Age X Task	12, 208	1.160	0.314	0.06	12, 100	1.267	0.250	0.13
Posture X Task	4, 208	6.554	< 0.001**	0.11	4, 100	0.568	0.687	0.02
Age X Posture X Task	12, 208	1.303	0.219	0.07	12, 100	0.919	0.531	0.10

[ξ]The %jitter values were transformed into log(log(%jitter)+1) for females and log(%jitter) for males before being submitted to ANOVA tests. The female transformed data failed the Box's M test of equal variance. Both female and male transformed data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

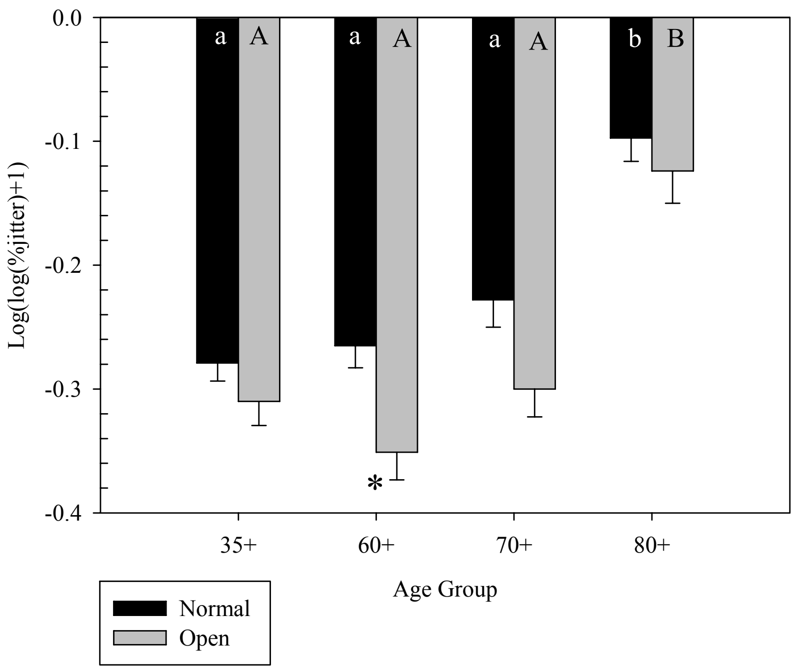


Figure 8. Means and standard errors of the transformed %jitter values for sustained vowel /a/ in females across postures (normal vs. open) and tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups combined. Significantly different means between age groups are marked with different letters and those between jaw postures are marked with an asterisk ("*").

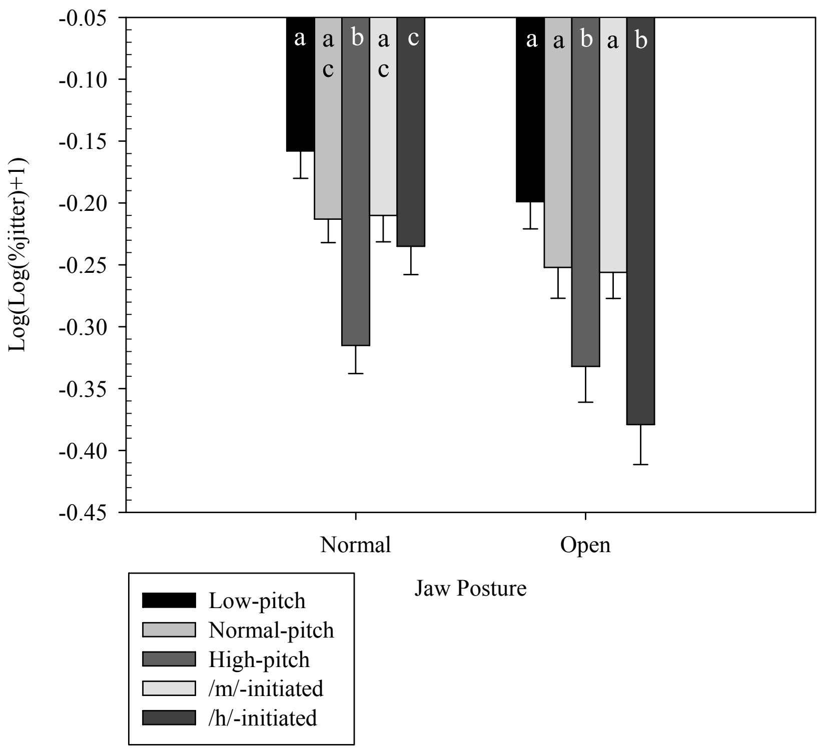


Figure 9. Means and standard errors of the transformed %jitter values for sustained vowel /a/ in females across postures (normal vs. open) and tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups combined. Significantly different means are marked with different letters.

For males, the mean transformed %jitter value was significantly higher in the normal than the open jaw posture. As for the task effect found in males, follow-up pairwise multiple comparisons revealed that low-pitch condition was associated with the highest mean transformed %jitter and high-pitch condition with the lowest mean transformed %jitter value (see Figure 10). This finding is similar to the finding for the normal jaw posture condition in females as previously described.

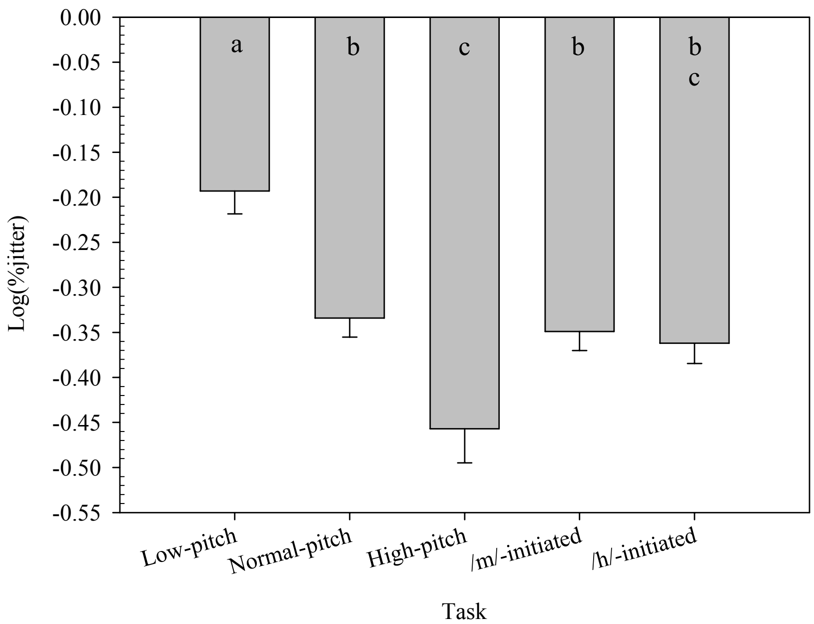


Figure 10. Means and standard errors of the transformed %jitter values for sustained vowel /a/ in males across tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups and postures combined. Significantly different means are marked with different letters.

Although the three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVA conducted on the transformed %jitter values for the sustained vowel /a/ in males failed to reveal a significant age group effect, a planned post-hoc one-way ANOVA on Ranks conducted on the %jitter measures in males with all tasks and postures combined revealed a significant age group effect ($H = 15.11$, $df = 3$, $p = 0.002$) and pairwise multiple comparisons using Dunn's method showed that %jitter was significantly higher in the 80+ age group than in the 60+ and 70+ age groups (see Figure 11). Furthermore, the mean %jitter for the isolated vowel /a/ sustained by males at normal pitch increased from 0.441 for the 35+ age group to 0.537 for the 80+ age group (Appendix 17). These %jitter values compare favourably with reports of the aging-induced change in %jitter values in a study of healthy males by Orlikoff (1990), which showed an increase of the mean %jitter value for the vowel /a/ from 0.461 in young males (ages 26-33) to 0.625 in older males (ages 68-80).

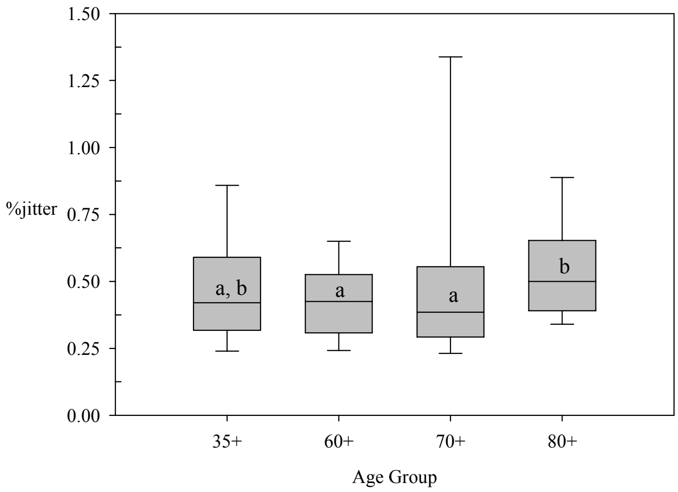


Figure 11. Box plot of the %jitter measures across age groups for sustained vowel /a/ in males, with the median shown as the line within the box, the 25th and 75th percentiles as the lower and upper boundaries of the box, and the 10th and 90th percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters.

5.1.2.1.2 Embedded Vowels

As shown in Table 7, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the transformed %jitter measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects for both females and males and a significant age group by vowel by posture interaction effect for males.

For females, open jaw posture resulted in a significantly lower mean transformed %jitter than normal jaw posture. Pairwise multiple comparisons for the vowel effect revealed that /a/ showed a significantly higher mean transformed %jitter than all the other vowels, /ɔ/, /u/, and /i/ (see Figure 12).

The post hoc planned one-way ANOVA on Ranks conducted on the female %jitter measures revealed a significant age group effect ($H = 19.141$, $df = 3$, $p < 0.001$). As shown in Figure 13, pairwise multiple comparisons using Dunn's method revealed that the youngest age group (35+) had a significantly lower mean %jitter than the oldest age group (80+).

Table 7. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on %jitter[ξ] for embedded vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	2.066	0.116	0.11	3, 25	0.509	0.680	0.06
Posture	1, 52	38.829	< 0.001**	0.43	1, 25	14.533	< 0.001**	0.34
Vowel	3, 156	44.450	< 0.001**	0.46	3, 75	27.798	< 0.001**	0.53
Age X Posture	3, 52	0.271	0.846	0.02	3, 25	0.502	0.684	0.06
Age X Vowel	9, 156	0.913	0.516	0.05	9, 75	0.842	0.580	0.09
Posture X Vowel	3, 156	0.199	0.897	0.004	3, 75	1.374	0.257	0.05
Age X Posture X Vowel	9, 156	1.251	0.268	0.07	9, 75	2.211	0.030*	0.21

[ξ] The %jitter values were transformed into log(%jitter) before being submitted to ANOVA tests. The female transformed data failed the Box's M test of equal covariance. Both female and male transformed data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

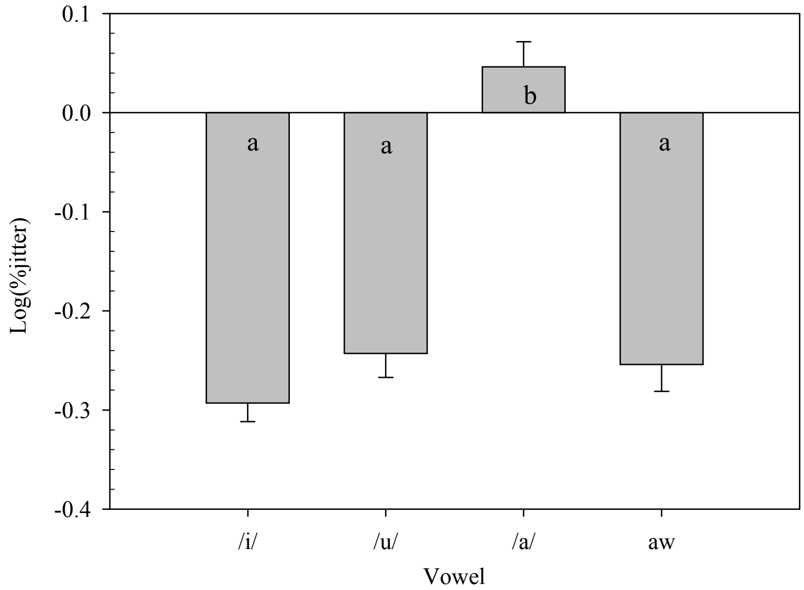


Figure 12. Means and standard errors of the transformed %jitter values for embedded vowels in females across vowels (/i, u, a, ɔ/; Note: the vowel /ɔ/ is written as "aw" in the graph) with all age groups and postures combined. Significantly different means are marked with different letters.

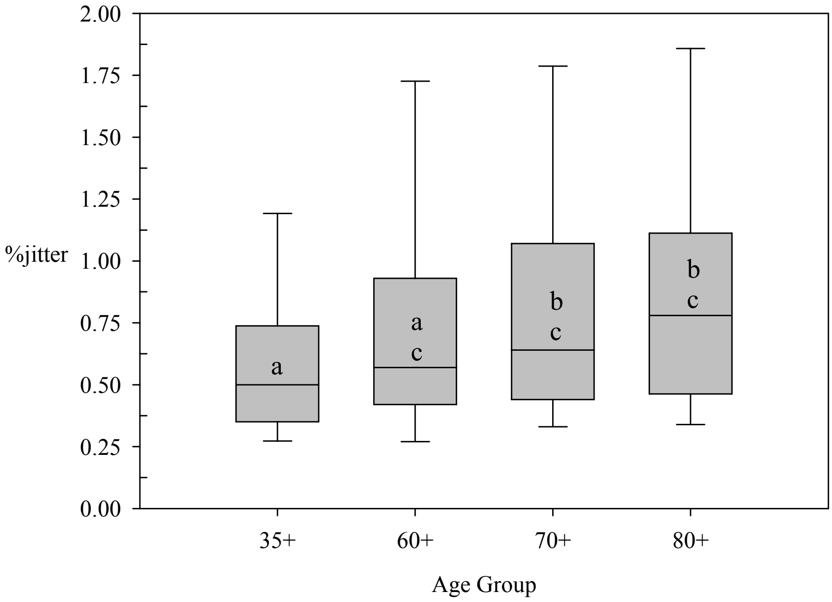


Figure 13. Box plot of the %jitter measures across age groups for embedded vowels in females, with the median shown as the line within the box, the 25th and 75th percentiles as the lower and upper boundaries of the box, and the 10th and 90th percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters.

For males, the mean transformed %jitter for the embedded vowels was significantly lower in the open jaw posture than in the normal jaw posture. Pairwise multiple comparisons for the embedded vowels in males showed that, like the finding in females, /a/ showed a significantly higher mean transformed %jitter than all the other vowels, /ɔ/, /u/, and /i/ (see Figure 14). As for the age group effect found to be insignificant in the three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVA conducted on the %jitter values in males, post hoc planned one-way (4 age groups) ANOVA on Ranks also failed to reveal any age group effect (H = 2.547, df = 3, p = 0.467).

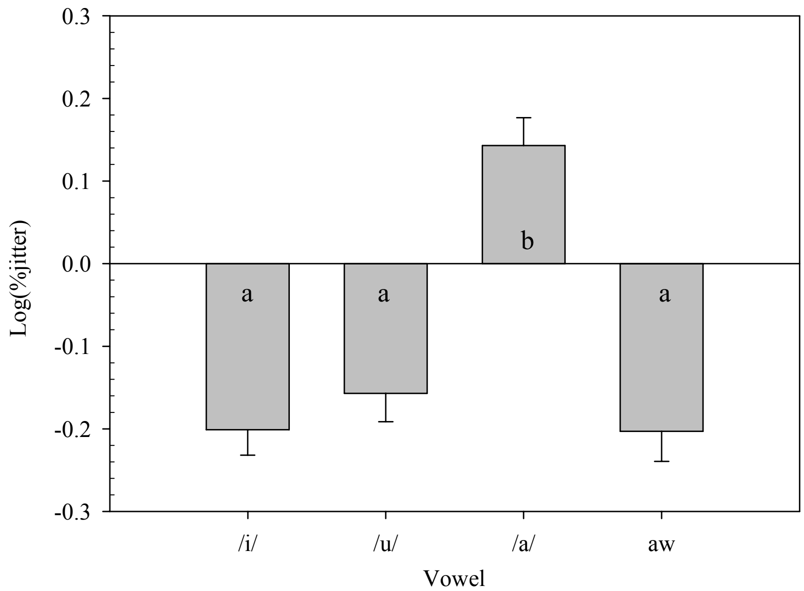


Figure 14. Means and standard errors of the transformed %jitter values for embedded vowels in males across vowels (/i, u, a, ɔ/; Note: the vowel /ɔ/ is written as "aw" in the graph) with all age groups and postures combined. Significantly different means are marked with different letters.

In summary, %jitter increased with age for adults for females in both sustained and embedded vowels, with the oldest age group (80+) showing a significantly higher mean %jitter than the other younger age groups. The age group effect on %jitter for males was found only for the sustained vowel /a/ but for embedded vowels, with the oldest age group (80+) showing the highest %jitter in the sustained vowel /a/. As for the jaw posture effect, the open jaw posture was significantly lower than the normal jaw posture regardless of gender, age group, task, and vowel. The sustained /a/ finding of the task effect on %jitter shows that %jitter was higher, for both females and males, in the low-pitch condition than in the other conditions, narmely, the normal-pitch, high-pitch, /m/-initiated, and /h/-initiated conditions. The embedded vowel finding of the vowel effect on %jitter shows that the vowel /a/, for both females and males, had significantly higher mean %jitter than the other three vowels, /i/, /u/, and /ɔ/.

5.1.2.2 Percent Shimmer

Statistical results are reported for %shimmer extracted from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the embedded vowels /i, ɔ, u, a/ separately.

5.1.2.2.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Table 8, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the transformed %shimmer for the sustained vowel /a/ revealed significant age group, posture, task effects and posture by task and age group by posture by task interaction effects for females and significant posture and task effects and posture by task interaction effect for males.

Table 8. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on %shimmer[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	7.037	< 0.001**	0.29	3, 25	0.458	0.714	0.05
Posture	1, 52	39.883	< 0.001**	0.43	1, 25	12.474	0.002**	0.33
Task	4, 208	31.911	< 0.001**	0.38	4, 100	23.903	< 0.001**	0.49
Age X Posture	3, 52	2.535	0.067	0.13	3, 25	1.071	0.379	0.11
Age X Task	12, 208	1.416	0.160	0.16	12, 100	1.061	0.410	0.11
Posture X Task	4, 208	47.421	< 0.001**	0.48	4, 100	35.046	< 0.001**	0.58
Age X Posture X Task	12, 208	3.436	< 0.001**	0.17	12, 100	0.812	0.638	0.09

[ξ]The %shimmer values were transformed into log(log(%shimmer)+1) before being submitted to ANOVA tests. Both female and male transformed data failed the Box's M test of equal covariance and the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

For females, open jaw posture was found to be associated with a significantly higher mean transformed %shimmer than normal jaw posture only in the /h/-initiated condition (see Figure 15). As shown in Figure 15, no significant task difference on the transformed %shimmer was found with the normal jaw posture. However, with open jaw posture, the /h/-initiated condition exhibited a significantly higher mean transformed %shimmer than the other conditions (i.e., normal-pitch, low-pitch, high-pitch, and /m/-initiated condtions).

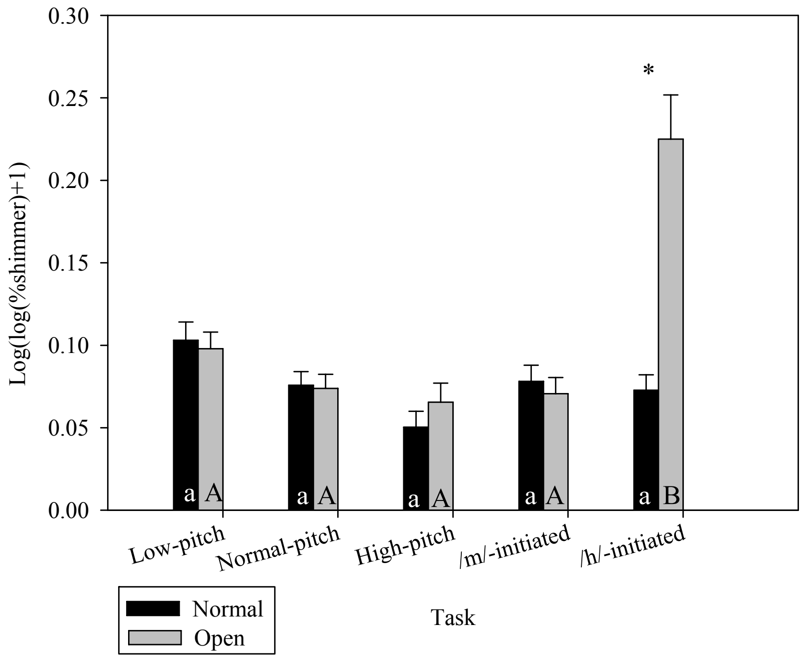


Figure 15. Means and standard errors of the transformed %shimmer values for sustained vowel /a/ in females across tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups combined. Significantly different means between tasks are marked with different letters and those between jaw postures are marked with an asterisk ("*").

As for the age group effect in females, pairwise multiple comparisons using the Dunn's method showed that the two younger age groups (35+ and 60+) had a significantly lower mean %shimmer than the two older age groups (70+ and 80+) and the 70+ age group had a significantly lower mean %shimmer than the 80+ age age group (see Figure 16). Descriptive statistics also showed that the mean %shimmer value for the isolated vowel /a/ sustained by females at normal pitch increased from a mean of 1.36 in the 35+ age group to a mean of 2.51 in the oldest 80+ age group (Appendix 17).

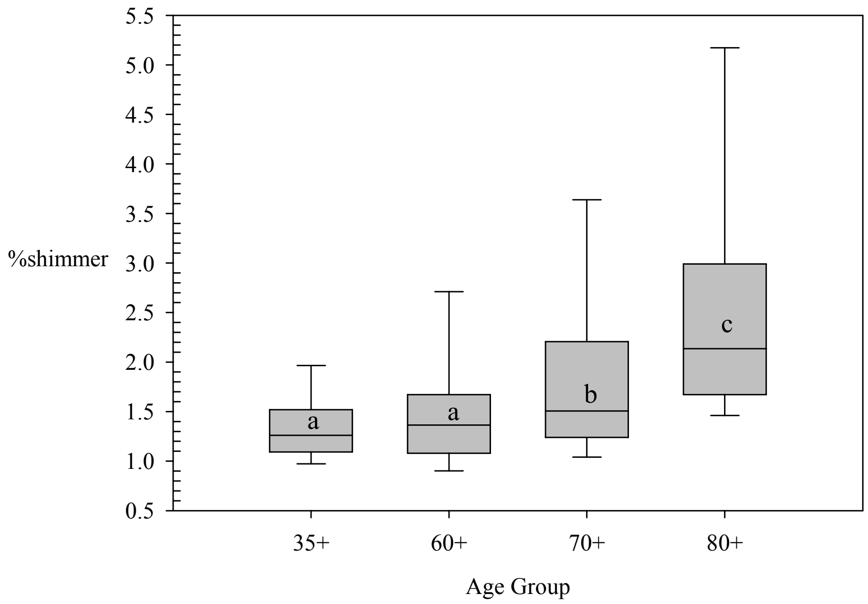


Figure 16. Box plot of the %shimmer measures across age groups for the sustained vowel /a/ in females, with the median shown as the line within the box, the 25th and 75th percentiles as the lower and upper boundaries of the box, and the 10th and 90th percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters.

For males, open jaw posture was found to be associated with a significantly higher mean transformed %shimmer than normal jaw posture only in the /h/-initiated condition (see Figure 17). This finding was the same as the fining from the sustained vowel /a/ in females as previously described. With both normal and open jaw postures, the low-pitch condition had a significantly higher mean transformed %shimmer value than the high-pitch condition. With open jaw posture, the finding in females that the /h/-initiated condition exhibited a significantly higher mean transformed %shimmer than the other conditions (i.e., normal-pitch, low-pitch, high-pitch, and /m/-initiated condtions) as previously described was also present in males (see Figure 17).

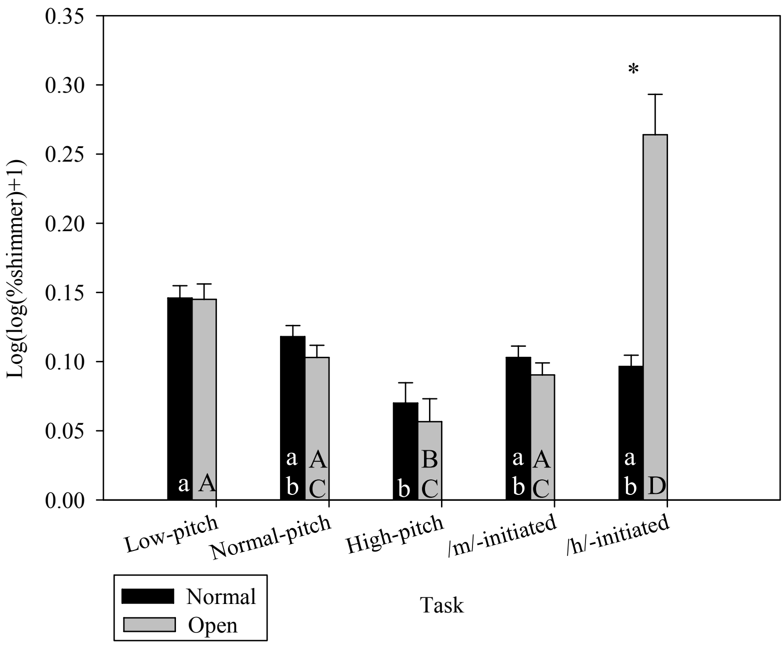


Figure 17. Means and standard errors of the transformed %shimmer values for sustained vowel /a/ in males across tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with all age groups combined. Significantly different means between tasks are marked with different letters and those between jaw postures are marked with an asterisk (“*”).

Although descriptive statistics showed that the mean %shimmer of the isolated vowel /a/ sustained by males increased from a mean of 1.96 in the 35+ age group to 2.21 in the 80+ age group (Appendix 17), no significant age group effect was found from a one-way (4 age groups) ANOVA on Ranks conducted on the %shimmer measures of the sustained vowel /a/ with all age groups and tasks combined in males ($H = 3.847$, $df = 3$, $p = 0.278$).

5.1.2.2.2 Embedded Vowels

As shown in Table 9, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the transformed %shimmer measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects for both females and males.

For both females and males, the open jaw posture showed a significantly lower mean transformed %shimmer value than the normal jaw posture. Pairwise multiple comparisons of the %shimmer revealed that for both females and males, /a/ showed a significantly higher mean %shimmer than all the other vowels, /i/, /u/, and /ɔ/ (see Figure 18).

Table 9. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on %shimmer$^{\xi}$ for embedded vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	1.890	0.143	0.10	3, 25	1.753	0.182	0.17
Posture	1, 52	28.060	< 0.001**	0.35	1, 25	9.091	0.006*	0.27
Vowel	3, 156	12.233	< 0.001**	0.20	3, 75	11.733	< 0.001**	0.32
Age X Posture	3, 52	0.205	0.892	0.01	3, 25	2.052	0.132	0.20
Age X Vowel	9, 156	1.258	0.264	0.07	9, 75	1.310	0.246	0.14
Posture X Vowel	3, 156	1.772	0.155	0.03	3, 75	2.538	0.063	0.09
Age X Posture X Vowel	9, 156	1.322	0.230	0.07	9, 75	1.072	0.394	0.11

$^{\xi}$The %shimmer values were transformed into log(%shimmer) before being submitted to ANOVA tests. The female transformed data failed the Box's M test of equal covariance and the Mauchly's test of sphericity. The male transformed data passed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

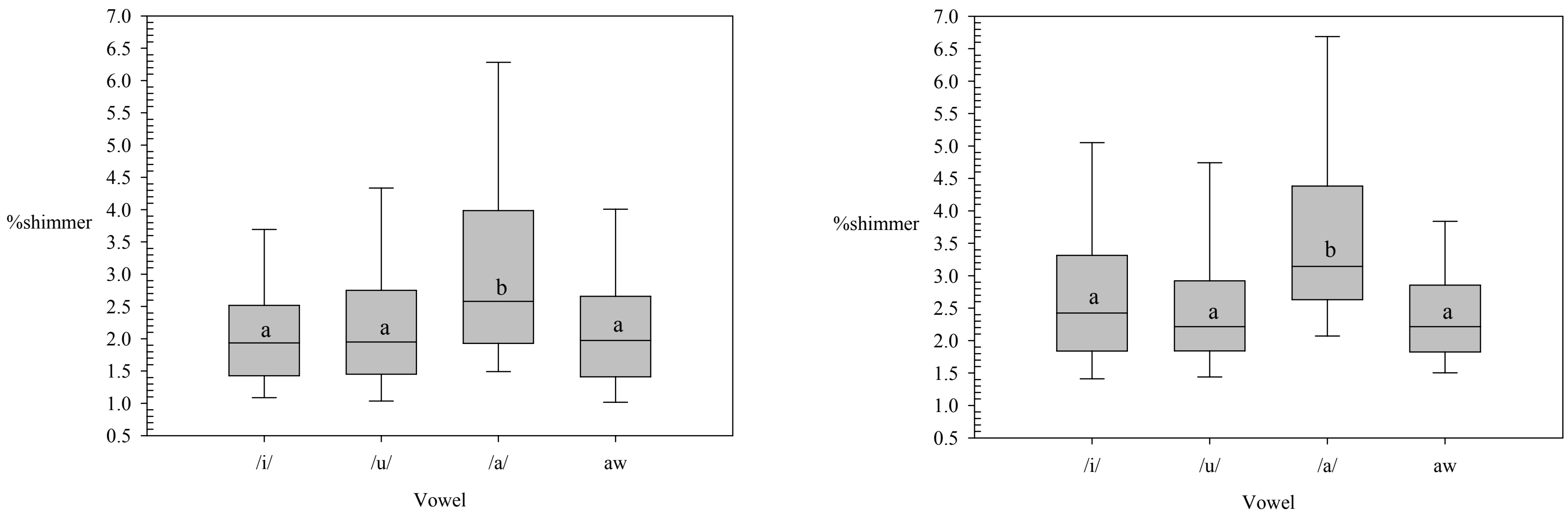


Figure 18. Box plot of the %shimmer measures across vowels for embedded vowels in females (left graph) and males (right graph), with the median shown as the line within the box, the 25th and 75th percentiles as the lower and upper boundaries of the box, and the 10th and 90th percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters.

In summary, %shimmer increased with age for adults in both sustained vowel /a/ and embedded vowels for females while the age group effect on %shimmer was less consistent for males. For the vowel /a/ initiated with /h/, open jaw posture led to a significantly higher mean %shimmer than normal jaw posture for both females and males. However, for embedded vowels, open jaw posture led to a significantly lower mean %shimmer than normal jaw posture for both females and males. The task effect on %shimmer for females and males showed that it was significantly higher in the low-pitch condition than in the other conditions (i.e., normal-pitch, high-pitch, /m/-initiated, and /h/-initiated). The vowel effect on %shimmer for both females and males showed that it was highest for the vowel /a/.

5.1.2.3 SNR

Statistical results for SNR obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and on the four embedded vowels /i, ɔ, u, a/ were reported separately.

5.1.2.3.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Table 10, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the SNR measures for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed significant age group and task effects and age group by task interaction effect for females but only a significant task effect for males.

Table 10. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on SNR[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	2.901	0.044*	0.14	3, 25	0.311	0.817	0.04
Posture	1, 52	0.162	0.689	0.003	1, 25	0.950	0.339	0.04
Task	4, 208	26.302	< 0.001**	0.34	4, 100	27.704	< 0.001**	0.53
Age X Posture	3, 52	1.416	0.249	0.08	3, 25	0.943	0.435	0.10
Age X Task	12, 208	2.119	0.017*	0.11	12, 100	1.616	0.099	0.16
Posture X Task	4, 208	0.866	0.485	0.02	4, 100	0.528	0.716	0.02
Age X Posture X Task	12, 208	0.577	0.859	0.03	12, 100	1.427	0.166	0.15

[ξ]The female raw data failed the Box's M test of equal covariance. Both female and male raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

For females, post hoc results showed that SNR was significantly lower in the oldest 80+ age group than the other age groups across all tasks (see Figure 19), suggesting voice deterioration with age for adults in females. As for the task effect on SNR, post hoc testing revealed that high-pitched /a/ was significantly higher, in all age groups except for the youngest age group (i.e., 35+), than the low-pitched condition for females (see Figures 19), indicating an improvement in SNR with a raised pitch.

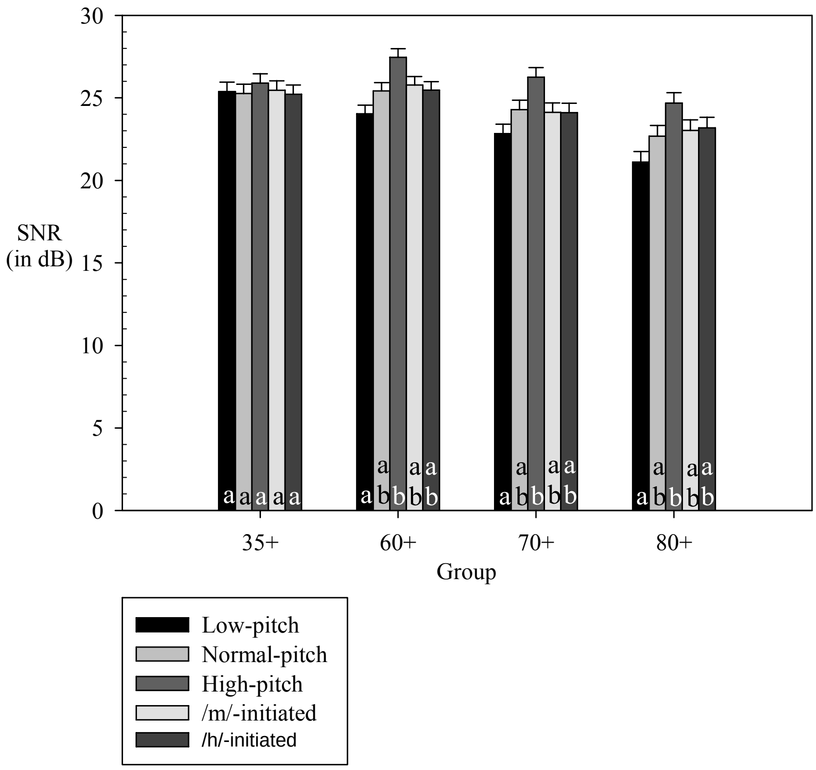


Figure 19. Means and standard errors of the SNR measures for the sustained vowel /a/ in females across age groups (35+, 60+, 70+, and 80+) and tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated, and /h/-initiated) with both jaw postures combined. Significantly different means are marked with different letters.

For males, the high-pitched /a/ was also found to be associated with an average SNR value significantly higher than all the other tasks except for the /m/-initiated condition (see Figure 20). It can be observed from the three ptich conditions that increased pitch was associated with increased SNR.

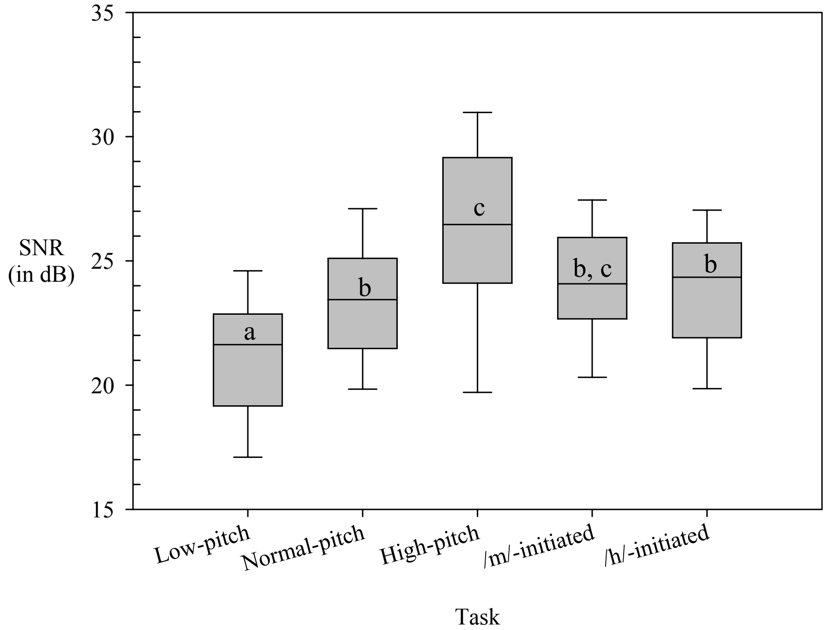


Figure 20. Box plot of the SNR measures across tasks (low-pitch, normal-pitch, high-pitch, /m/-initiated), and /h/-initiated for the sustained vowel /a/ in males, with the median shown as the line within the box, the 25^{th} and 75^{th} percentiles as the lower and upper boundaries of the box, and the 10^{th} and 90^{th} percentiles as the lower and higher whiskers. Significantly different medians are marked with different letters

5.1.2.3.2 Embedded Vowels

As shown in Table 11, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the SNR measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects and posture by vowel interaction effect for both females and males.

For females, the average SNR was found to be significantly higher in an open jaw posture condition than in the normal jaw posture condition for the vowel /u/ both females and males (see Figure 21). As for the vowel effect, post hoc testing revealed that the embedded vowel /a/ had a significantly lower SNR than all the other vowels in both normal and open postures for both females and males (See Figure 21).

Table 11. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on SNR[ξ] for embedded vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	0.547	0.652	0.03	3, 25	1.428	0.258	0.15
Posture	1, 52	21.578	< 0.001**	0.29	1, 25	14.970	0.001**	0.38
Vowel	3, 156	101.773	< 0.001**	0.66	3, 75	63.114	< 0.001**	0.72
Age X Posture	3, 52	0.430	0.733	0.02	3, 25	1.481	0.244	0.15
Age X Vowel	9, 156	1.831	0.067	0.10	9, 75	1.358	0.222	0.14
Posture X Vowel	3, 156	6.985	< 0.001**	0.12	3, 75	3.929	0.012*	0.14
Age X Posture X Vowel	9, 156	1.272	0.256	0.07	9, 75	1.479	0.171	0.15

[ξ]The female raw data passed the Box's M test of equal covariance. The male raw data passed but the female raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

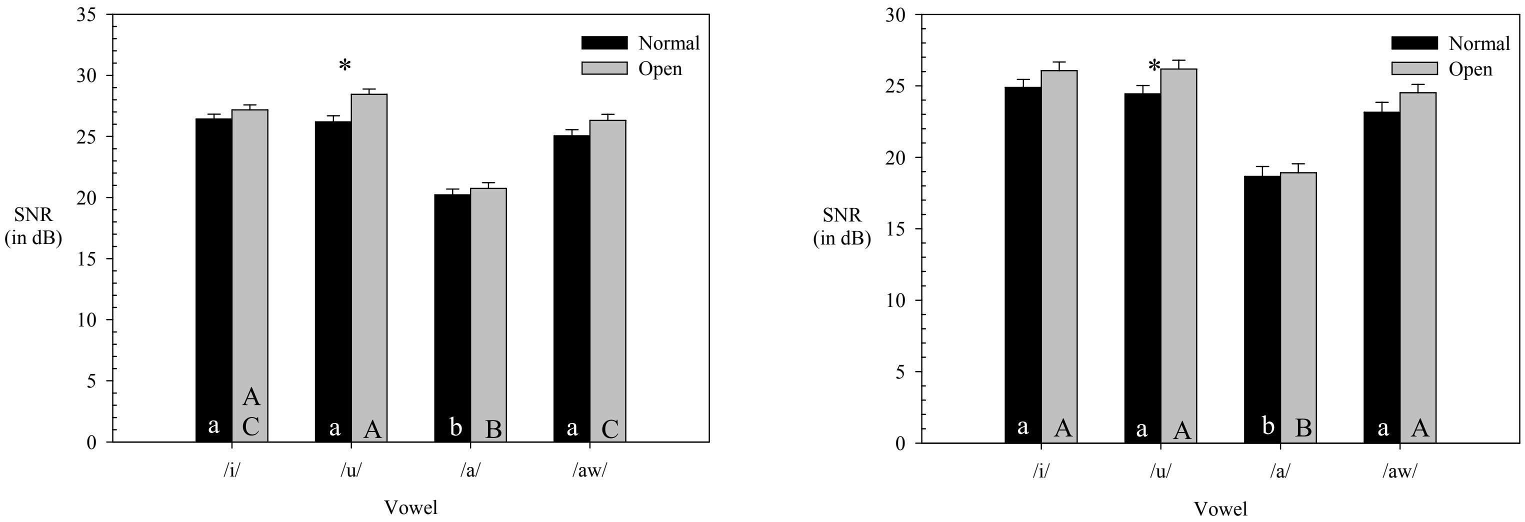


Figure 21. Means and standard errors of the SNR measures for embedded vowels across jaw postures (normal and open) and vowels (/i, u, a, ɔ/; Note: the vowel /ɔ/ is written as "aw" in the graph) with all age groups combined for females (left graph) and males (right graph). Significantly different means between vowels are marked with different letters and those between jaw postures are marked with an asterisk ("*").

5.1.3 Formant Frequencies

Statistical results are reported separately for the formant frequencies F1 and F2 obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the vowels /i, ɔ, u, a/ embedded in the sentence "We saw two cars."

5.1.3.1 F1

Statistical results are reported for measures of F1 frequency derived from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and those from the embedded vowels /i, ɔ, u, a/.

5.1.3.1.1 Vowel /a/ Sustained In a One-Syllable Task

Results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the F1 measures for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed significant task effect and age group by task interaction effect for females and significant task effect for males (see Table 12). Females F1 was found to be highest in the youngest age group (35+) and lowest in the oldest age group (see Appendix 37.16). In contrast, for males F1 was highest in the oldest age groups and lowest in the youngest age group (see Appendix 37.17). Normal-pitched /a/, /ma/ and /ha/ did not differ significantly in F1, but both low-pitched and high-pitched /a/ tended to be lower for both genders (see Appendices 37.18 and 37.19). As shown in Appendix 41.11, F1 was significantly higher in an open jaw posture condition than in a normal jaw posture condition for females.

Table 12. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on F1[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	1.017	0.393	0.06	3, 25	1.529	0.232	0.16
Posture	1, 52	3.842	0.055	0.07	1, 25	0.398	0.534	0.02
Task	4, 208	13.977	< 0.001**	0.21	4, 100	22.829	< 0.001**	0.48
Age X Posture	3, 52	1.109	0.354	0.06	3, 25	1.046	0.389	0.11
Age X Task	12, 208	3.169	< 0.001**	0.16	12, 100	1.457	0.154	0.15
Posture X Task	4, 208	1.593	0.177	0.03	4, 100	1.204	0.314	0.05
Age X Posture X Task	12, 208	0.882	0.566	0.05	12, 100	1.115	0.357	0.19

[ξ]The F1 values were transformed into square(F1) for females before being submitted to the ANOVA test. The female transformed data failed the Box's M test of equal covariance. Both female transformed and male raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

5.1.3.1.2 Embedded Vowels

As shown in Table 13, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the F1 measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects and posture by vowel interaction effect for both females and males.

For females, post hoc testing of the age group effect in the embedded vowels revealed, as shown in Appendix 39.19, a significant difference between 35+ age group and two older age groups (60+ and 80+), showing a tendency to decrease with age for adults. For males, post hoc testing of the age by vowel interaction effect revealed that the older two age groups (70+ and 80+) did not differ significantly from each other but were statistically different from the 35+ and 60+ age groups (see Appendix 39.22).

Table 13. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on F1[ξ] for embedded vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	2.474	0.072	0.13	3, 25	0.612	0.613	0.07
Posture	1, 52	5.949	0.018*	0.10	1, 25	13.582	0.001**	0.35
Vowel	3, 156	502.545	< 0.001**	0.91	3, 75	313.165	< 0.001**	0.93
Age X Posture	3, 52	0.015	0.997	0.001	3, 25	0.519	0.673	0.06
Age X Vowel	9, 156	0.769	0.645	0.04	9, 75	1.793	0.083	0.18
Posture X Vowel	3, 156	24.994	< 0.001**	0.33	3, 75	7.562	< 0.001**	0.23
Age X Posture X Vowel	9, 156	1.059	0.396	0.06	9, 75	1.508	0.161	0.15

[ξ] The female raw data failed the Box's M test of covariance. Both female and male raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

Post hoc testing of the posture by vowel interaction effect for females showed that F1 was higher with an open jaw posture than with a normal jaw posture for the vowels /ɔ/ and /a/ but a significant difference between open and normal jaw postures was only found for the vowel /a/ (see Appendix 39.20). Post hoc testing of the posture by vowel interaction effect for males showed that F1 was higher with an open jaw posture than with a normal jaw posture for the vowels /i/, /ɔ/, and /a/ but a significant difference between open and normal jaw postures was only found for the vowel /ɔ/ (See Figure 21 in Appendix 39).

As shown in Appendix 40, results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on F1 obtained from the embedded vowel /a/ showed significant posture effects but no significant age or age by posture interaction effect for both females and males. For both females and males F1 was significantly higher in an open jaw posture condition than in the normal jaw posture condition regardless of age group (Figure 4.12).

As shown in Appendix 50, results from the two-way (4 age groups x 4 vowels) mixed model ANOVAs conducted on F1 obtained from the embedded vowels (/i, ɔ, u, a/) in normal and open jaw posture revealed significant vowel effects for both females and males, but no age group effects or age group by vowel interaction effects for either gender. Post hoc reporting showed the same vowel effect on F1 for both genders, that in both normal an open jaw posture there were no significant differences between the vowels /i/ and /u/, but they were both significantly different from the vowels /ɔ/ and /a/, which in turn, were significantly different from each other.

In summary, the age group effect on F1 showed that it was lower for the oldest 80+ female age group and higher in the three oldest male age groups for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), and lower for the three oldest female age groups in the four embedded vowels. Formant one was higher in an open jaw posture for females in the isolated vowel /a/ in normal pitch, and for both females and males in the embedded vowel /a/ in normal pitch. For both females and males in the four embedded vowels, posture by vowel interaction effects, in an open jaw posture, /a/ and /ɔ/ increased, /u/ decreased, and /i/ remained relatively constant. Task effects for both females and males on F1 showed it was higher in normal-pitch, /ma/ and /ha/ than in low-pitch and high-pitch. Age by vowel interaction effects showed F1 to be highest for the vowel /a/, and in descending order /u/, /i/ and /ɔ/ with the older two age groups significantly different from the two younger groups. An age group effect was not found on F1 for the four embedded vowels.

5.1.3.2 F2

Statistical results are reported for measures of F2 frequency derived from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and those from the embedded vowels /i, ɔ, u, a/.

5.1.3.2.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Table 14, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the F2 measures for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed significant age group, posture, and task effects for females and significant posture and task effects for males. For females, post hoc results showed that F2 was significantly lower in the 60+ age group than in the elderly groups and for males, F2 was significantly lower in the 35+ age group than the three oldest groups (see Appendices 37.20 and 37.21). As for the posture effect, F2 was found to be significantly lower in an open jaw posture condition than in the normal jaw posture condition for females (see Appendix 37.22). For the task effect, post hoc testing revealed that low-pitched /a/ significantly differed from the normal-pitched /a/, /ma/, /ha/ and high-pitched /a/ for F2 regardless of gender (see Appendices 37.23 and 37.24).

Table 14. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on F2[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	2.884	0.044*	0.14	3, 25	1.404	0.265	0.14
Posture	1, 52	34.019	< 0.001**	0.40	1, 25	5.522	0.027*	0.18
Task	4, 208	12.252	< 0.001**	0.19	4, 100	18.233	< 0.001**	0.42
Age X Posture	3, 52	0.032	0.992	0.002	3, 25	0.476	0.702	0.05
Age X Task	12, 208	1.683	0.072	0.09	12, 100	0.903	0.547	0.10
Posture X Task	4, 208	2.393	0.052	0.04	4, 100	1.440	0.226	0.05
Age X Posture X Task	12, 208	1.366	0.184	0.07	12, 100	1.600	0.104	0.16

[ξ] Both female and male raw data failed the Mauchly's test of sphericity. The female raw data failed the Box's M test of equal covariance. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

Results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the F2 measures obtained from the isolated vowel /a/ sustained at normal pitch revealed statistically significant age group effects for females and significant posture effects for both females and males but no significant age by posture effects for either gender. Post hoc testing of the age group effect showed that for females F2 was significantly lower for the 60+ age group than the other three age groups (Appendix 41.13) although F2 did tend to lower from the 35+ age group (1425Hz) to the 80+ age group (1402Hz). As shown in Appendix 41.14, F2 was significantly lower in an open jaw posture condition than in a normal jaw posture condition for both females and males.

5.1.3.2.2 Embedded Vowels

As shown in Table 15, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the F2 measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant posture and vowel effects and posture by vowel interaction effect for both females and males.

Post hoc testing of the age by vowel interaction effect revealed that all pairwise comparisons between age groups were significant but the direction of the aging-induced changes varied by vowel. For example, as shown in Appendices 39.23 and 39.24, the two older age groups (70+ and 80+), as compared with the youngest age group (35+), showed a significantly higher F2 in /a/ but a significantly lower F2 in /i/.

Table 15. Summary results of the 3-way (age group X posture X vowel) mixed model ANOVAs conducted on F2[ξ] for embedded vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	0.611	0.611	0.03	3, 25	0.464	0.710	0.05
Posture	1, 52	16.796	< 0.001**	0.24	1, 25	6.076	0.021*	0.20
Vowel	3, 156	813.445	< 0.001**	0.94	3, 75	306.256	< 0.001**	0.93
Age X Posture	3, 52	0.616	0.608	0.03	3, 25	0.986	0.415	0.11
Age X Vowel	9, 156	1.507	0.150	0.08	9, 75	1.555	0.145	0.16
Posture X Vowel	3, 156	32.864	< 0.001**	0.39	3, 75	2.810	0.045*	0.10
Age X Posture X Vowel	9, 156	0.424	0.921	0.02	9, 75	0.527	0.850	0.06

[ξ]The female raw data failed the Box's M test of equal covariance but passed the Mauchly's test of sphericity. The male raw data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

Results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on F2 obtained from the embedded vowel /a/ showed a significant posture effect for females, a significant age group effect for both females and males, and no significant age by posture interaction effects for either females or males. Post hoc testing of the posture effect for females revealed that F2 was significantly lower in an open jaw posture condition than in the normal jaw posture condition (Appendix 41.15). Post hoc testing of the age group effect for females revealed F2 was significantly lower in the 60+ age group compared to the other three age groups (Appendix 41.16). The age group effect for males showed that F2 was lower in the youngest age group than the three older groups (see Appendix 41.17).

In summary, F2 tends to decrease for /i/ and increase for /a/ with age for adults for both males and females. The age group effects on F2 for males showed that it generally increased with age for adults for the embedded vowel /a/ and for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). In an open jaw posture, F2 was lower for females and males in the isolated vowel /a/ in normal pitch. It was also lower for females in the embedded vowel /a/, in the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), and for the four embedded vowels. In an open jaw posture for females in the four embedded vowels, F2 decreased for /ɔ/, /u/, and /a/ and increased for /i/. The task effect on F2 showed that for both females and males, F2 was significantly lower in low-pitch, with the other four conditions, normal-pitch, /ma/, /ha/ and high-pitch showing very similar values. An age group effect was not found on F2 for the individual four embedded vowels.

5.1.4 Vowel Space Area

Statistical results are reported for measures of vowel space area obtained from the F1 and F2 frequencies of the vowels /i, ɔ, u, a/ embedded in the sentence "We saw two cars." produced in two jaw postures (normal vs. open). Vowel space area was calculated from the mean F1 and F2 measurements from each of the four embedded vowels. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed separately for females and males on vowel space area are presented in Table 16 and are shown in Figure 22.

As shown in Table 16 results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs on vowel space area revealed significant posture effects but no significant age or two-way age by posture interaction effects for both females and males.

Table 16. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the measures of vowel space area using the four vowels /i, ɔ, u, a/ embedded in the sentence "We saw two cars." produced in normal and open jaw postures (normal and open). Number of participants; females = 56 and males = 29, n = the number of tokens (2 posture x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture Effect
			Vowel Space Area	
Females	112	$F(3,52) = 0.340$, $p = 0.377$	$F(1,52) = 38.470$, $\mathbf{p < 0.001}$**	$F(3,52) = 1.181$, $p = 0.326$
Males	58	$F(3,25) = 1.734$, $p = 0.186$	$F(1,25) = 12.700$, $\mathbf{p = 0.002}$*	$F(3,25) = 1.149$, $p = 0.349$

*Significant at 0.05 level
**Significant at 0.005 level

Vowel space area was found to be significantly larger in an open jaw posture condition than in the normal jaw posture condition for both females and males (see Figure 22). In an open jaw posture vowel space area increased by a factor of 1.21 for females and increased by a factor of 1.29 for males, from a normal jaw posture.

Examination of vowel space areas of three subgroups of the full group of study participants, i.e., speakers of New Zealand, British and American English separately, vowel space area were also found to increase in an open jaw posture although this was only significant for female and male speakers of New Zealand English [$F(1,33) = 16.844$, $p < 0.001$] and [$F(1,12) = 11.542$, $p = 0.005$] respectively, and for female and male speakers of British English [$F(1,4) = 25.607$, $p = 0.007$] and [$F(1,5) = 8.202$, $p = 0.035$] respectively, though not for either female or males speakers of American English [$F(1,5) = 1.208$, $p = 0.322$] and [$F(1,1) = 37.706$, $p = 0.103$ respectively (see Appendix 21).

In summary, vowel space area was found to be significantly larger in an open jaw posture for both females and males from the four embedded vowels. However, although this statistical significance was found, closer examination of the data showed that this was true only for female and male speakers of New Zealand English and British English and not from the U.S. English speakers. An age group effect on vowel space area was not found for either females or males.

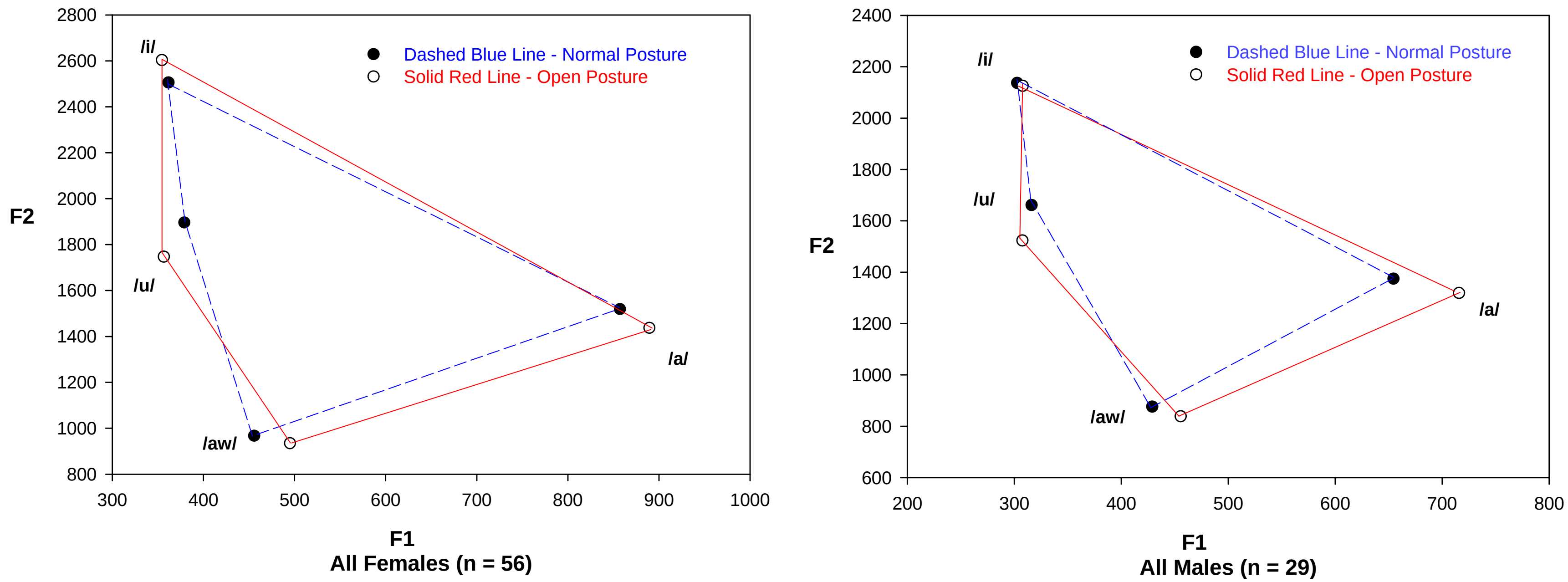


Figure 22. Vowel space for normal and open jaw postures in females (left graph) and males (right graph). Note: the vowel /ɔ/ is written as "aw" in the following graphs.

5.1.5 H1H2

Statistical results are reported for measures of H1-H2 amplitude difference obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). As shown in Table 17, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the H1H2 measures for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed significant posture and task effects for females and significant posture and task effects and posture by task interaction effect for males. For females, post hoc results showed that H1-H2 amplitude difference was higher in the three oldest groups and was significantly higher in the 70+ age group than in each of the other three age groups (see Appendix 37.25). A different pattern was identified for males where H1-H2 amplitude difference was found to be lower in the 60+ and 70+ age groups and higher for the 35+ and 80+ age groups (Appendix 37.26). As for the posture effect, H1-H2 amplitude difference was found to be significantly lower in an open jaw posture condition than in the normal jaw posture condition for both females and males (Appendix 37.27). For the task effect, post hoc testing revealed that normal-pitched /a/, /ma/, /ha/ and low-pitch /a/ did not differ significantly in H1-H2 amplitude difference for females however high-pitched /a/ was found to be significantly lower (See Appendix 37.28). As shown in Appendix 37.29, for males post hoc testing revealed that for H1-H2 amplitude difference, normal-pitched /a/, /ma/ and /ha/ did not significantly whereas low-pitched and high-pitch /a/ were significantly higher and lower respectively.

Results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the measures of H1-H2 amplitude difference obtained from the isolated vowel /a/ sustained at normal pitch revealed statistically significant posture effects for females but not for males, and no age or age by posture interactive effects for either gender. As shown in Appendix 41.21, for females H1-H2 was significantly lower in an open jaw posture condition than in a normal jaw posture condition. As shown in Appendix 17, mean H1-H2 amplitude difference for females increased with age from the 35+ age group (7.574dB) to the 70+ age group (10.113dB) and then decreased in the oldest 80+ age group (7.626dB). The age group effect on H1-H2 amplitude difference for males showed mixed results, being higher in the 35+ (11.850dB) and 80+ (10.9534dB) age groups and lower in the 60+ (8.453 dB) and 70+ (7.685 dB) age groups.

Table 17. Summary results of the 3-way (age group X posture X task) mixed model ANOVAs conducted on H1H2[ξ] for sustained vowels in females and males separately.

	Female				Male			
Effect	df	F	p	η^2_p	df	F	p	η^2_p
Age	3, 52	1.359	0.266	0.07	3, 25	1.817	0.170	0.18
Posture	1, 52	36.415	< 0.001**	0.41	1, 25	190.907	< 0.001**	0.88
Task	4, 208	12.661	< 0.001**	0.20	4, 100	81.75	< 0.001**	0.77
Age X Posture	3, 52	1.514	0.222	0.08	3, 25	0.704	0.558	0.08
Age X Task	12, 208	0.985	0.464	0.05	12, 100	0.999	0.455	0.11
Posture X Task	4, 208	0.504	0.733	0.01	4, 100	95.543	< 0.001**	0.79
Age X Posture X Task	12, 208	1.676	0.074	0.09	12, 100	1.250	0.260	0.13

[ξ]The H1H2 values were transformed into square root (H1H1) for males before being submitted to the ANOVA test. The female raw data failed the Box's M test of equal covariance. Both female raw and male transformed data failed the Mauchly's test of sphericity. As the adjusted tests (e.g., Greenhouse-Geisser test) yielded the same results as the standard test, only the standard results are shown.
*Significant at 0.05 level
**Significant at 0.005 level

In summary, the age group effects on the H1-H2 amplitude difference showed that in the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), it was significantly higher for females in the 70+ age group and lower for males in the 60+ and 70+ age groups. In an open jaw posture H1-H2 was lower for females in the isolated vowel /a/ in normal pitch and for both females and males in the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). The task effects showed that H1-H2 amplitude difference for females was lowest in the low-pitch and high-pitch conditions, and for males it was highest in low-pitch, and lowest in high-pitch condition.

5.1.6 VOT

Statistical results are reported separately for the VOT measured from the word “cars” and from the word “two” embedded in the sentence “We saw two cars.”

5.1.6.1 VOT Measured from the Word “cars”

As shown in Table 18, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on VOT obtained from the temporal difference between the consonant /k/ and the embedded vowel /a/“in the word “car”” from the sentence "We saw two cars." showed significant age and posture effects but no significant age by posture interaction effects for both females and males. For the posture effect, VOT was found to be significantly longer in an open jaw posture condition than in the normal jaw posture condition for both females and males (Appendix 41.18a). For females, VOT was found to be longer in the three older age groups than in the 35+ age group (Appendix 41.19). Descriptive statistics showed that VOT increased from the 35+ age group to the oldest 80+ age group. However, this change was not linear. As shown in Appendix 17, VOT increased from the 35+ age group (84.4 ms) to the 60+ age group (104.3 ms) where it then shortened slightly in the 70+ age group (mean 102.1 ms) and shortened again in the 80+ group (mean 94.7 ms). Post hoc testing of the age group effect in females revealed only a significant age group difference between the 35+ and 60+ age groups. For males, post hoc reporting revealed that VOT shortened with age from the 35+ age group to the 80+ age group as observed in Appendix 41.20a. There was a more consistent pattern of change in VOT for males where VOT decreased for males with age from the 35+ age group (mean 102.9 ms) to the 80+ age group (mean 61.9 ms). Post hoc testing of the age group effect for males showed that VOT was significantly lower in the 80+ age group than in the 35+ and 60+ age groups (see Appendix 41.20a).

5.1.6.2 VOT Measured from the Word "two"

As shown in Table 18, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on VOT obtained from the temporal difference between the consonant /t/ and the embedded vowel /u/ in the word "two"" from the sentence "We saw two cars." showed significant age and posture effects only for males and no significant age by posture interaction effects for either females or males. For the posture effect, VOT was found to be significantly longer with an open jaw posture than with a normal jaw posture for males (Appendix 41.18b). For males, post hoc reporting revealed that VOT was significantly longer in the 35+ age group than in the other three older age groups (see Appendix 41.20b). Descriptive statistics show VOT is longest in the 35+ age group (mean = 103.3 ms) and shortest in the oldest 80+ age group (mean = 64.8 ms).

Table 18. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on VOT measures for /ka/ and /tu/ from the sentence 'We saw two cars'. Number of participants: females = 56 and males = 29, n = the number of tokens (2 posture x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture Effect
		VOT		
Embedded /ka/				
Females	112	$F(3,52) = 3.198$, **$p = 0.031$***	$F(1,52) = 6.513$, **$p = 0.014$***	$F(3,52) = 0.718$, $p = 0.546$
Males	58	$F(3,25) = 7.992$, **$p < 0.001$****	$F(1,25) = 5.629$, **$p = 0.026$***	$F(3,25) = 2.139$, $p = 0.121$
Embedded /tu/				
Females	112	$F(3,52) = 1.703$, $p = 0.178$	$F(1,52) = 1.890$, $p = 0.175$	$F(3,52) = 0.223$, $p = 0.880$
Males	58	$F(3,25) = 4.609$, **$p = 0.011$***	$F(1,25) = 5.041$, **$p = 0.034$***	$F(3,25) = 2.361$, $p = 0.095$

In summary, VOT tended to decrease with age for adults, especially for males (see Appendices 41.20a and 41.20b). However, for females, VOT-/ka/ was significantly shorter in the youngest group (35+) than the other three older age groups (60+, 70+, and 80+). An open jaw posture resulted in an increase of VOT for both females and males.

5.1.7 Vowel and Sentence Durations

In this section, statistical results are reported for sentence and vowel durations measured from the sentence "We saw two cars." The Results from the series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs for sentence length measured from the sentence "We saw two cars." and vowel length from each of the four individual embedded vowels /i, ɔ, u, a/ in normal and open jaw posture are shown in Table 19. The means and standard deviations for measures showing a significant vowel, age group, or jaw posture effect are shown in Figure 23. Mean sentence length and vowel duration times are shown in Appendix 22. Sentence durations in normal jaw posture from the test sentence are presented in Appendix 23.

As shown in Table 19, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on duration times obtained from measures of sentence and measures of the four embedded vowels at normal pitch revealed statistically significant posture effects for sentence length and for all four vowels though no significant age group effects or interaction effects were found for either females or males. Sentence duration was significantly longer in an open jaw posture condition than in a normal jaw posture condition for both females and males (see Figure 23.1). Vowel duration times were found to be statistically longer in an open jaw posture condition than in a normal posture condition for both females and males across all age groups and for all four vowels (See Figures 23.2 and 23.3).

Table 19. Results from the two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on measures of the duration of the sentence "We saw two cars." and vowel length from the embedded vowels /i, ɔ, u, a/. Number of participants: females = 56 and males = 29, n = the number of tokens (2 posture 5 tasks x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture
			Sentence Duration	
Females	112	F(3,52) = 1.477, p = 0.323	F(1,52) = 117.363, p < **0.001****	F(3,52) = 1.407, p = 0.251
Males	58	F(3,25) = 0.297, p = 0.828	F(1,25) = 47.457, p < **0.001****	F(3,25) = 0.620, p = 0.608
			/i/ Duration	
Females	112	F(3,52) = 1.352, p = 0.268	F(1,52) = 119.032, p < **0.001****	F(3,52) = 0.567, p = 0.639
Males	58	F(3,25) = 0.509, p = 0.680	F(1,25) = 47.553, p < **0.001****	F(3,25) = 0.352, p = 0.788
			/ ɔ / Duration	
Females	112	F(3,52) = 0.715, p = 0.548	F(1,52) = 42.831, p < **0.001****	F(3,52) = 2.728, p = 0.053
Males	58	F(3,25) = 0.053, p = 0.984	F(1,25) = 41.330, p < **0.001****	F(3,25) = 1.015, p = 0.403
			/u/ Duration	
Females	112	F(3,52) = 0.292, p = 0.831	F(1,52) = 136.650, p < **0.001****	F(3,52) = 0.948, p = 0.424
Males	58	F(3,25) = 0.456, p = 0.716	F(1,25) = 48.423, p < **0.001****	F(3,25) = 0.310, p = 0.818
			/a/ Duration	
Females	112	F(3,52) = 1.416, p = 0.249	F(1,52) = 76.577, p < **0.001****	F(3,52) = 0.949, p = 0.424
Males	58	F(3,25) = 0.337, p = 0.799	F(1,25) = 45.526, p < **0.001****	F(3,25) = 1.446, p = 0.253

*Significant at 0.05 level
**Significant at 0.005 level

Figure 23. Bar charts of the significant effects of jaw posture on sentence and vowel duration for females (n = 56) and males (n = 29).

Notes: (1) The vowel /ɔ/ is written as "aw" in the following graphs.
(2) Groups significantly different are marked with different letters.
(3) "*" indicates a significant difference between the paired groups.

Figure 23.1 - Females and Males
Sentence Duration
Posture Effect

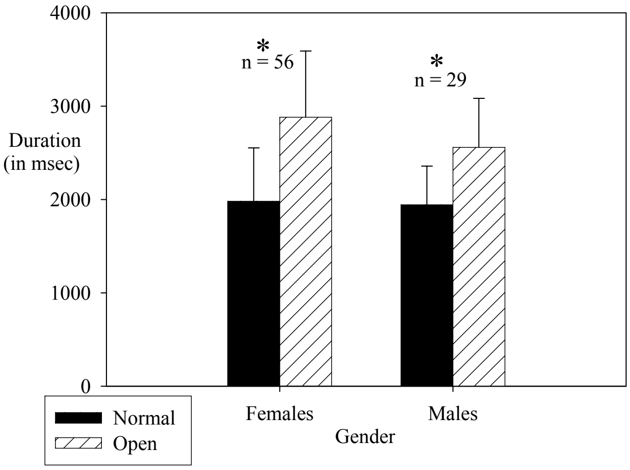


Figure 23.2 - Females
Vowel Duration
Posture Effect

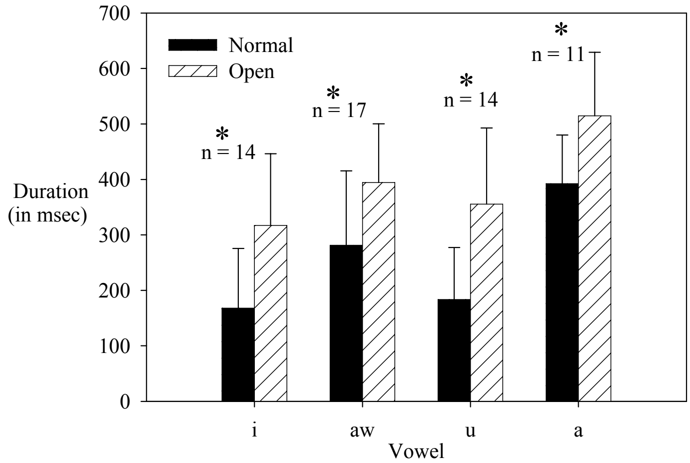
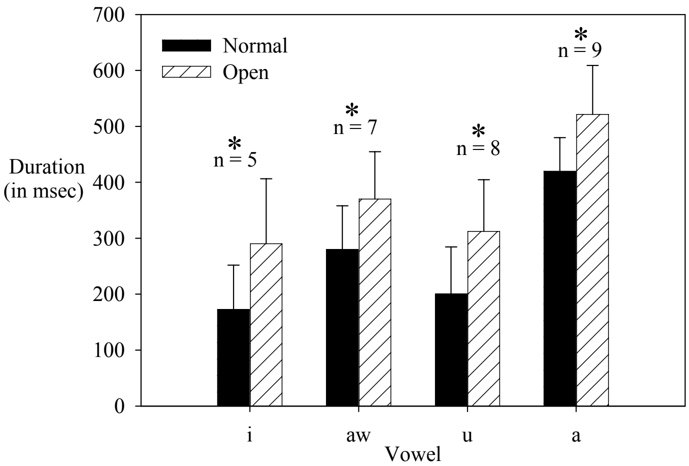


Figure 23.3 - Males
Vowel Duration
Posture Effect



Although no significant age group effect on sentence duration was found, mean sentence length tends to increase continuously with age for females from 1,747 ms in the 35+ age group to 2,214 ms in the 80+ age group and, for males, mean sentence length decreased from 1,972 ms in the 35+ age group and 2,016 ms in the 60+ age group to 1,867 ms the oldest 80+ age group (Appendix 23). When sentence and word durations were compared between normal and open jaw productions, mean sentence duration increased by a factor of 1.40, mean duration time for the word "cars" increased by a factor of 1.20, and mean duration time for the word "two" increased by a factor of 1.50.

In summary, an open jaw posture was associated with an increase of vowel and sentence durations for both females and males. Sentence duration was not significantly different between age groups although an increasing trend for females and a decreasing trend for males with age for adults were observed.

5.2 EGG Measures

Results from a series of three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVAs performed on the EGG measures (F0, SQ and OQ) are presented in Appendix 42 for the /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and those from a series of three-way (2 jaw postures X 4 age groups X 4 vowels) in Appendix 44 for the embedded vowels /i, ɔ, u, a/. Results from a series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the EGG measures are presented in Appendix 46 for the vowel /a/ sustained in each of the one-syllable tasks (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and for each of the four embedded vowels /i, ɔ, u, a/. The means and standard deviations for the EGG measures showing a significant task, age group, or jaw posture effect are presented in Appendix 43 for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in Appendix 45 for the embedded vowels /i, ɔ, u, a/.

5.2.1 F0

Statistical results for the F0 measured from EGG signals (EGG F0) are reported separately for measures extracted from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and for those from the embedded vowels /i, ɔ, u, a/.

5.2.1.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Appendix 42, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on the EGG F0 for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed significant age, posture, and task effects, but no significant two-way or three-way interaction effect for both females and males. For males, post hoc results showed that EGG F0 was significantly higher in the two oldest age groups than in the two younger age group (see Appendix 43.2), with a significant difference between 35+ and 60+ age groups. As for the posture effect, EGG F0 was found to be significantly higher in an open jaw posture than in a normal jaw posture for both females and males (see Appendix 43.5). For the task effect, post hoc testing revealed that (1) normal-pitched /a/, /ma/, and /ha/ did not differ significantly in EGG F0, and that (2) low-pitched /a/ and high-pitched /a/ were significantly lower and higher, respectively for both females and males (see Appendices 43.6 and 43.7).

As shown in Appendix 46, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on EGG F0 obtained from the isolated vowel /a/ sustained at normal pitch revealed statistically significant age group effects for males and significant posture effects and no significant age by posture interaction effects for both females and males. For males, post hoc results showed that EGG F0 was significantly higher in the 70+ and 80+ age groups than in the younger groups (see Appendix 43.3). An open jaw posture was found to have a significantly higher EGG F0 than the normal jaw posture for both females and males (Appendix 43.4).

5.2.1.2 Embedded Vowels

As shown in Appendix 44, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on EGG F0 obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant age and vowel effects for females, and significant vowel and age by posture effects for males, but no significant three-way interaction effects for either females or males.

For females, post hoc testing for the age group effect on EGG F0 obtained from the embedded vowels showed that EGG F0 was significantly higher in the 35+ age group than in the three elderly groups (Appendix 45.1). As for the age by posture interaction effect found for males, EGG F0 was not significantly different between age groups with the normal posture but, with an open jaw posture, was significantly higher in the oldest age group (80+) than in the other three younger age groups (see Appendix 45.4). Post-hoc testing for the vowel effect on EGG F0 obtained from the embedded vowels revealed that both females and males exhibited a significantly higher EGG F0 in the high vowel /i/ than in the low vowel /a/ and shared the same pattern of having the highest EGG F0 for /i/, followed in descending order by /u/, /ɔ/, and /a/ (Appendices 45.2 and 45.3).

As shown in Appendix 47, results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the EGG F0 measures obtained from the embedded vowel /a/ revealed a statistically significant posture effect for females and significant age, posture, and age by posture interaction effects for males. For females, EGG F0 was significantly higher in an open jaw posture than in a normal jaw posture (Appendix 45.5). For males, a significant difference between open jaw and normal jaw postures was only found to the oldest age group (80+), with an open jaw posture also being associated with a higher EGG F0. For males, as shown in Appendix 45.6, no age group difference was found with a normal jaw posture but, with an open jaw posture, EGG F0 was the highest in the oldest group (80+), followed in descending order by the 70+, 60+, and 35+ age groups, with a significant difference between 80+ and 70+ age groups and between 80+, as well as 70+, and the other two younger age groups (35+ and 60+).

In summary, EGG F0 tends to decrease for females (see Appendices 43.1 and 45.1) and increase for males (see Appendices 43.2, 43.3, and 45.4). These findings are consistent with the acoustic data from the current study and previous findings reported in the literature regarding the age group effect on F0. In addition, for both females and males, an open jaw posture was found to result in an increase of EGG F0 in both sustained vowel phonation (see Appendices 43.4 and 43.5) and in embedded vowels (see Appendices 45.4, 45.5, and 45.6). For both females and males, /a/ was found to be significantly lower in EGG F0 than the other three vowels (see Appendices 45.2 and 45.3). The task effect on EGG F0 showed that for both females and males, EGG F0 was significantly lower in low-pitch (except that /ma/ and low-pitch are not significantly different in females) and significantly higher in high-pitch than the three other conditions, namely, normal-pitch, /ma/, and /ha/, which showed no significant differences among them (see Appendices 43.6 and 43.7).

5.2.2 SQ

Statistical results are reported separately for SQ values measured from the vowel /a/ sustained in a one-syllable task and from the embedded vowels /i, ɔ, u, a/.

5.2.2.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Appendix 42, results from three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVAs on SQ for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed a significant age group effect but no significant two-way or three-way interaction effect for both females and males. Post hoc testing of the age group effect revealed that SQ was significantly lower in the 60+ age group than in the two oldest age groups for females (see Appendix 43.8) while, for males, SQ was significantly higher in the 60+ and 70+ age groups than in the 35+ and 80+ age groups (Appendix 43.9).

As shown in Appendix 46, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on SQ obtained from the isolated vowel /a/ sustained at normal pitch showed no significant effect of age, posture, or age by posture interaction for either females or males.

5.2.2.2 Embedded Vowels

As shown in Appendix 44, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs conducted on the SQ measures obtained from the four vowels /i, u, a, ɔ/ embedded in a sentence showed significant age group effects but no significant posture, task, two-way or three-way interaction effects for both females and males.

For females, post hoc testing for the aging effect for the embedded vowels revealed that SQ was significantly higher in the 60+ age group than in the 35+ age group but SQ did not increase significantly with age for adults after age 70 years (Appendix 45.7). For males, SQ was also significantly higher in the 60+ age group than in the 35+ age group but SQ did not increase significantly with age for adults after 80+ (Appendix 45.8).

Results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the SQ measures obtained from the embedded vowel /a/ showed no age, posture or age, by posture interaction effects for both females and males (see Appendix 47).

In summary, no significant jaw posture on SQ was found. The direction of SQ changes due to aging was not consistent for females although the youngest female group (35+) tends to show a lower SQ than the older groups in both sustained and embedded vowels (see Appendices 43.8 and 45.7). For males, however, results from both sustained and embedded vowels shows that SQ tends to increase after age 60 years and then decrease after age 80 years (see Appendices 43.9 and 45.8).

5.2.3 OQ

Statistical results are reported separately for OQ values measured from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the embedded vowels /i, ɔ, u, a/.

5.2.3.1 Vowel /a/ Sustained In a One-Syllable Task

As shown in Appendix 42, results from three-way (2 jaw postures X 4 age groups X 5 tasks) mixed model ANOVAs on OQ for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) revealed a significant age group effect but no significant jaw posture, task, or two-way or three-way interaction effect for both females and males. Post hoc testing of the age group effect revealed OQ was lower in the two oldest age groups for females (Appendix 43.10). This contrasted with the results for males where OQ lowered in the 60+ age group and then increased in the 70+ and 80+ age groups (Appendix 43.11).

As shown in Appendix 46, results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on OQ obtained from the isolated vowel /a/ sustained at normal pitch revealed a statistically significant posture effect for females but no significant age or age by posture interaction effects for both females and males. Post hoc reporting for females showed OQ to be significantly higher in an open jaw posture condition than in the normal jaw posture condition (Appendix 43.12).

5.2.3.2 Embedded Vowels

As shown in Appendix 44, results from three-way (2 jaw postures X 4 age groups X 4 vowels) mixed model ANOVAs on OQ from the vowels /i, ɔ, u, a/ embedded in a sentence revealed a significant age group effect for both females and males but no significant jaw posture, vowel, two-way or three-way interaction effects for both females and males. For females, post hoc results for the embedded vowels revealed OQ decreased with age, with the two older age groups showing significantly lower OQs than the youngest age group (Appendix 45.9). For males, OQ was also highest in the 35+ age group but a significant age group difference was only found between the 35+ and 60+ age groups (Appendix 45.10). However, results from follow-up two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the OQ measures obtained from the embedded vowel /a/ in normal pitch showed no age, posture, or age by posture interaction effects for both females and males (see Appendix 47).

In summary, an age group effect was found on measures of OQ obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the four embedded vowels for females, showing that OQ was the highest in the youngest age groups (35+) and tended to decrease with age for adults. However, this decreasing trend due to aging appears to reverse for the elderly men above age 70 years. An open jaw posture effect was found, in females, to increase OQ for the isolated vowel /a/ sustained at normal pitch.

5.3 Aerophone Measures

Results from a series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on the Aerophone measures, including SPL and MFR obtained from the sustained /a/ and air pressure, airflow rate, and laryngeal resistance obtained from the /pa-pa-pa-pa-pa/ production, to determine the effects of age group, jaw posture, and age group by jaw posture interaction on these measures are summarized in Appendix 48 for females and males separately. For the Aerophone measures extracted from the sustained vowel /a/ phonation, a total of 170 (85 participants X 2 jaw postures) time durations were obtained, ranging from 0.42 to 3.1 seconds (Mean = 1.47 sec, SD = 0.54).

Appendix 49 shows the means and standard deviations of the Aerophone measures, including SPL, MFR, and air pressure, in each comparison group for the isolated vowel /a/ sustained at normal pitch, along with the acoustic measures of F0, %jitter, %shimmer, SNR, F1, F2, H1-H2 amplitude difference, and VOT obtained from the isolated vowel /a/ sustained at normal pitch recorded during the acoustic-EGG-facial tracking recording session.

5.3.1 SPL

As shown in Appendix 48, there was a significant posture effect on the SPL measures obtained from the isolated vowel /a/ sustained at normal pitch but no significant age group or age group by posture interaction effect for either females or males. For both females and males, the open jaw posture resulted in a significantly higher SPL than the normal jaw posture (see Appendix 41.22). Although no significant age group effect was found, there was a tendency for the SPL to decrease with age in females. As shown in Appendix 17 (with normal and open jaw combined), mean SPL was highest in the youngest female age group (35+) than in the three older age groups.

5.3.2 MFR

As shown in Appendix 48, a significant jaw posture effect was found for the MFR measures obtained from the isolated vowel /a/ sustained at normal pitch for both females and males. Mean Flow Rate was found to be significantly higher in an open jaw posture condition than in a normal jaw posture condition for both females and males (See Appendix 41.23). Although no significant age group was found, it could be observed from Appendices 49.17 and 49.18 that MFR tends to decrease with age for males in both jaw postures (Appendix 49.18) while it tends to decrease with age for females until the age of 80 years, after which MFR starts to increase (Appendix 49.17).

5.3.3 Air Pressure and LAR

As shown in Appendix 48, a significant jaw posture effect on the air pressure and air flow rate obtained from the /pa-pa-pa-pa-pa/ production in normal pitch was found for females but not for males. Both airflow rate and air pressure were found to be significantly higher in an open jaw posture than in a normal jaw posture for females (See Appendices 41.24 and 41.25). No significant effect of age group, jaw posture, or their interactions was found for the laryngeal resistance measures in either females or males.

In summary, an open jaw posture resulted in a significantly higher MFR and SPL for both females and males and a significantly higher air pressure in females. No significant aging effect on MFR, SPL, or air pressure although some tendency for SPL to decrease with age for adults can be observed in females.

5.4 Jaw Displacement

In this section, statistical results are reported on the maximum degree of jaw displacement during phonation that was measured from a baseline starting with the jaw in a neutral position at the start of phonation with the lips closed.

As shown in Appendix 48, results from a series of two-way (2 jaw postures X 4 age groups) mixed model ANOVAs conducted on jaw displacement measured from the vowel

/a/ sustained at normal pitch revealed a statistically significant posture effect and no age or age by posture interaction effects for both females and males. As shown in Appendix 41.26, jaw displacement was significantly greater in an open jaw posture for both females and males. It can be observed from Appendix 41.26 that while males and females exhibited relatively the same degree of jaw displacement in normal jaw posture, females showed a greater increase of jaw displacement than males with an open jaw posture.

Females had a greater mean jaw opening distance (i.e., the distance between the starting closed neutral jaw position with the lips closed and the maximum open jaw distance) of 28.55mm compared to the male mean jaw opening distance of 24.63mm. A correlation between amount of change in F1 in normal and open jaw posture and the degree of jaw widening was higher for females ($r = 0.780$, $p = 2.146E-012$) than for males ($r = 0.390$, $p = 0.0446$).

5.5 Summary of Main Findings

This study examined (1) the sensitivity of the selected instrumental measures to identify age group effects in normally aging adults using acoustic, EGG and aerodynamic measures, (2) the effects of an open jaw posture on the voicing behaviours of normally aging adults, and (3) if instrumental measures can be useful in voice assessment of the elderly and to identify useful facilitative strategies, particularly the impact of an open jaw posture in the management of the aging voice. A list of experimental measures found to be sensitive to the age group or the jaw posture effect is presented in Appendices 34 and 35. The main findings in this instrumental investigation are:

1. **Age group effects:** The age group effect on the voice of normally aging adults was detected through a selection of instrumental measures. Fundamental frequency was found to be sensitive to aging effects in all phonatory productions measures, the sustained vowel /a/ in normal pitch, the vowel /a/ sustained in a one-syllable task (in normal, high, low pitch and /m/ and /h/ initiated), and in the four embedded vowels. The sustained vowel /a/ in normal pitch revealed greater aging effects for females with F0 (decreasing), %jitter and %shimmer (increasing), SNR (decreasing) and F2 (decreasing in the 60+ age group), than for males where only F0 (increased) showed significant age effects. From the vowel /a/ sustained in a one-syllable task, the age group effect was found for both females and males on F0, %jitter, F1, F2, H1-H2 amplitude difference, SQ, and OQ and, for females, age group effects were found on %shimmer and SNR. An age group effect on the four embedded vowels for females and males was found for F0, %jitter, SQ and OQ, and additionally for females on F1 and for males on %shimmer and SNR. Age group effects were found for both females and males on VOT-/ka/, where it increased for females and decreased for males, and, for males, on VOT-/tu/ which also decreased with age.

2. **Jaw posture effects:** An open jaw posture was shown to be useful for enhancing vocal stability (i.e., decreased %jitter, and %shimmer and increased SNR) and speech quality (decrease in H1-H2) in the geriatric voice. For both females and males, an open jaw posture resulted in an increase in F0, SNR, MFR, SPL, F1, VOT-/ka/, and vowel space area and a decrease in %jitter,

%shimmer, and F2. For females, an open jaw posture also resulted in an increase in air pressure, airflow rate (for /pa/ productions), and OQ. For males, an open jaw posture also led to increased VOT-/tu/. For both genders, an open jaw posture resulted in changes of F1 and F2 frequencies (e.g., increase in F1 and decrease in F2 frequencies for /a/) which lead to the expansion of vowel space area. As increases in vowel space area have been associated with better speech intelligibility, these findings suggest that the use of an open jaw posture may have a positive impact on geriatric speech. In addition, the H1-H2 amplitude difference decreased in an open jaw posture for both females and males, suggesting that an open jaw posture could result in a less breathy voice or a voice produced with thicker vocal folds.

3. **Instrumental measures as an Assessment Tool:**

Acoustic measures appear to be more sensitive than aerodynamic measures in detecting the aging effect for the vowel /a/ produced at normal pitch. However, both acoustic and aerodynamic measures were sensitive in detecting the impact of an open jaw posture on voice. The F0 measures obtained from the EGG signals are consistent with those from the acoustic measurements, showing that F0 increased in males and decreased in females with age for adults. Both SQ and OQ measured from EGG signals are useful for detecting the aging effect. In general, it was found that the age group effect as assessed with the selected instrumental measures was more evident in the female voice, while the sensitivity of these measures in detecting a jaw posture effect on voice appears to be similar for both females and males.

Chapter 6. DISCUSSION

The results from this study indicate that (1) jaw posture has an effect on a selection of acoustic measures related to phonatory stability, voice quality, and vowel clarity in healthy individuals across adult age groups, (2) the jaw posture effect on voicing can be related to changes in some physiological measures, and that (3) the age group difference in voice can be discerned through instrumental measurements.

6.1 Related to the Research Questions

The research questions as stated previously are threefold. Firstly, can an age group effect on voice for normally aging adults be detected through acoustic and physiological measures? Secondly, is there an effect on voicing behaviours when an "open jaw" posture is used? Specifically, is there evidence that the geriatric voice may be improved using an open jaw posture? Thirdly, can instrumental measures assist in voice assessment to identify useful facilitative strategies in the management of the aging voice?

This study employed changes in jaw position, i.e., from a normal speaking posture to an open jaw posture, to investigate the effect of jaw posture on phonatory measures in the voices of healthy older individuals. To evaluate how instrumental measures may be better used for voice assessment, the age group effect on the commonly used measures was also investigated. If changes in jaw posture are found to improve the aging voice and instrumental measures are able to detect characteristics of the aging voice, these would support the use of these facilitating strategies to the treatment of the geriatric voice and these instrumental measures could be applied to the clinical assessment and study of treatment efficacy in the management of the aging voice.

The results from this study have shown that an open jaw posture has a positive effect on a number of acoustic and physiological measurements of the geriatric voice. An open jaw posture was found in this study to result in an improvement in measures of phonatory stability, particularly as shown in the decrease of %jitter and %shimmer and the increase of SNR in women. Results have also shown that the vowel space area in both females and males increased in an open jaw posture. As research has shown that larger vowel space areas are associated with greater speech intelligibility, the finding that vowel space area increased in an open jaw posture provides evidence in support of an open jaw approach in improving speech quality. A widening of jaw opening also resulted in an increase in SPL in both genders. Since a lowering of SPL is one of the commonly cited features that identify a voice as being elderly, the finding that an open jaw posture would lead to an increase in SPL demonstrates the possible usefulness of this approach in the clinical treatment of the geriatric voice. In addition, except for a small increase in the female 80+ age group, measures of the H1-H2 amplitude difference decreased in an open jaw posture for both females and males, suggesting that an open jaw posture would result in a voice produced with thicker vocal folds. As vocal fold bowing, which often results in a breathy voice, has also been noted as one common feature of the aging voice in the literature, the increase in vocal fold thickness with jaw widening may be useful in improving voice quality.

As for the question of the usefulness of the experimental measures in detecting the age group effect on voice, this study has also yielded findings of objective measures demonstrating differences in phonatory behaviour as people age. Significant age group effects were found in this study for both genders on F0, VOT (/ka/), OQ, and SQ, and additionally, age differences were detected for females on %jitter, %shimmer, SNR, and F2 and VOT (/tu/) for males. Specifically, aging was found to result in a decrease of F0 for females and an increase of F0 for males. The average VOT was higher in older females and lower in older males for the velar plosive /k/ and vowel /a/ in the syllable /ka/ and lower in the older males for the alveolar plosive /t/ and the vowel /u/. For females, %jitter and %shimmer increased and SNR decreased in the oldest 80+ age group, and F2 (for /a/) in the 60+ age group was the lowest and significantly different from that in all the other three age groups (35+, 70+, and 80+).

The focus of the current study was the investigation of how these two features, age and jaw posture, may affect the voices of normally aging adults using a selection of instrumental measures of the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and the four vowels embedded in sentences. In the following discussion of these findings, age group effects and open jaw posture effects are presented separately.

6.2 Detection of the Aging Voice Through Instrumental Measures

The following sections describe the age group effects on a variety of acoustic variables obtained from four different types of phonatory production (1) from the vowel /a/ sustained at normal pitch, (2) from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), (3) from the vowel /a/ embedded in the word “cars” and (4) from the four vowels /i, ɔ, u, a/ embedded in a sentence. In addition, the physiological measures sensitive to the age group effect were also discussed.

6.2.1 Acoustic Findings

One of the challenges in drawing conclusions from acoustic and physiological data along the aging continuum is the variability of the aging process itself and its effect on phonation. There is considerable variation from one individual to another in the way people age. There is evidence that physiological age may be less related to chronological age (Mathieson, 2001) and that physical condition itself can play a critical role in phonatory behaviours (Ramig & Ringel, 1983). Research on the aging voice has shown greater variability between older age groups and younger age groups. Evidence of variability in phonatory measures in the elderly has been reported by Biever and Bless (1989), who found greater within-participant F0 variability in their study of 20 older women (ages 60-77) than in a group of 20 younger women (ages 22-28). Sweeting & Baken (1982) also reported greater variability in VOT in the older age groups (65+ years) than in their younger participant groups (25-39 years). They found that although the means did not differ significantly across age groups "the standard deviation of means did differ significantly; variability increased with age, both within subjects and between groups" (p. 129). Greater instability in the elderly voice was inferred from higher measures of standard deviations for F0 and amplitude perturbation quotient in the elderly as a group (Gorham-Rowan & Laures-Gore, 2006). Means and standard deviations for the experimental measures obtained from isolated vowel /a/ sustained at normal pitch are shown in Appendices 15 and 16.

6.2.1.1 F0

Examination of the F0 data revealed aging patterns on F0 showing that it decreased for females and increased in males as a function of age across the different phonatory tasks measured, i.e., the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the four embedded vowels. The results from this study are consistent with previous research in which similar gender patterns for F0 were found as people age, namely, that F0 decreases in women and increases in males (Biever & Bless, 1989; Linville et al., 1989; Higgins & Saxman, 1991; Colton & Casper, 1996; Linville, 1996, 2002; Mathieson, 2001; Ferrand, 2002).

Vocal fold vibratory behaviour is determined by a combination of mass, tension, and length; and a change to any of these features could subsequently affect vocal fold vibratory patterns, and as a result, affect the fundamental frequency. The gender differences in the aging patterns shown with the F0 measures may be attributed to the different ways in which females and males age physiologically, particularly in the way aging affects vocal fold mass. The decrease in F0 for females may be a consequence of the increase in vocal fold mass due to hormonal changes that occur during menopause (Abitbol et al., 1999) resulting in an increase in vocal fold mass. The increase in vocal fold mass in post-menopausal females results in a decrease in vibratory rate with fewer glottal cycles per second and hence, a lower F0. For males, the opposite effect occurs, showing reduced vocal fold mass from aging-induced atrophy of the internal thyroarytenoid that is characteristic of older males (Abitbol, 2006) and results in thinner vocal folds and a higher F0.

The results from this study support the existing body of evidence that instrumental measures are able to identify the changes in F0 that arise as a consequence of the normal aging process for both females and males.

6.2.1.2 Phonatory Stability

The results from this study demonstrated a significant age group effect on each of the three measures of phonatory stability, %jitter, %shimmer, and SNR from the vowel /a/ sustained in a normal pitch for females, although similar age group effects were not found for males. Though the perturbation measures for females did not change proportionally with age, there was a steady increase in %jitter and %shimmer and a decrease in SNR from the youngest to the oldest age groups. The greatest difference was found between the 80+ age group and the three younger age groups in all three perturbation measures. Examination of the data from the other phonatory conditions, including vowel /a/ sustained in a one-syllable task in various pitch levels or contexts (i.e., high, and low pitch and /m/ and /h/-initiated) and the four embedded vowels, also revealed age group effects on perturbation measures for both genders. These results contrast with Awan's (2004) finding that perturbation measures did not differ significantly among females in five age groups where the age range was 18-79. Differences in the results between the current study and Awan's (2004) study may be explained by the inclusion in the current study of women in the 80+ group (age range 80 – 91) where the significant differences were predominately found.

The performance of females in the 80+ age group in measures of phonatory stability from the vowel /a/ sustained at normal pitch, showed a pattern of worsening functionality in all three parameters, where %jitter and %shimmer increased and SNR decreased. It should be noted however, that large variation was found for %jitter and %shimmer within the two oldest female age groups (70+ and 80+), where the standard deviations, as a percentage of the mean, for %jitter reached 72% and 85% of the mean respectively, and the standard deviations for %shimmer for the two oldest female age groups reached 64% and 65% of the mean. Although we saw a small but steady progression of decreased phonatory stability with age for adults, it was only after age 80 that the greatest difference between this age group and the three younger age groups became apparent. These differences were found between females the 80+ age group in both the age group means and as well as in the greater within-group variation, and three younger groups. These findings are in line with the definition of presbyphonia by Benninger & Murray (2006) who place presbyphonia as beginning around age 80.

6.2.1.2.1 Percent Jitter

For females and males, %jitter increased (worsened) with age when measured from the vowel /a/ sustained at normal pitch, the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), and in the four embedded vowels (though starting from age 60+ for males in the embedded vowels). The age group effect on %jitter for females measured from the three phonatory production conditions was most evident in the oldest 80+ age group, where it was significantly higher, although with a large within-group variation. The age group effects on %jitter for males, as measured from the three different phonatory conditions, also showed that it increased (worsened) with age although it did not reach statistical significance.

In the current study, the age group effect on %jitter from the vowel /a/ sustained at normal pitch for females was principally observed in the difference between the oldest group, i.e., the 80+ group and the three younger age groups, 35+, 60+ and 70+. Also for females, the standard deviations for the 70+ and 80+ age groups were much larger than in the younger two groups, suggesting that the age group effects are more evident sometime after age 70. There was a steady incremental increase in %jitter with age for males though this was not statistically significant. In general, results show that %jitter tends to increase age with greater variability after age 70 for females. Previous research has however, presented differing opinions in regard to the effectiveness of %jitter as a reliable indicator of age. In some studies, no significant aging-induced differences were found (Ramig & Ringel, 1983; Ferrand, 2002) while other studies reported significant differences for %jitter between younger and older participants (Wilcox & Horii, 1980; Olikoff, 1990). These conflicting results raise the question of the usefulness of %jitter as a reliable indicator of aging-induced changes to the voice. However, findings from the current study indicate that age group differences in %jitter means and the within-group variability of means become greater after age 70, with much greater differences found for females after age 80.

In the current study, a statistically significant age group effect on %jitter was found for females. In fact, for the isolated vowel /a/ sustained at normal pitch, all three measures of phonatory stability, including %jitter, %shimmer and SNR, showed significant age group effects for females.

6.2.1.2.2 Percent Shimmer

The results for the perturbation measure %shimmer are similar to the findings described above for %jitter. There was a trend for %shimmer, measured either from sustained vowels or embedded vowels (except for males) to increase (worsen) with age for both females and males. Percent shimmer, as was found for %jitter, when measured from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), differed significantly for females in the 80+ age group from the three younger age groups. Greater within-group variation was found for females in the 70+ and 80+ age groups. This observation of aging patterns on %shimmer agrees with previous research where %shimmer has been reported to better differentiate between young and elderly voices than had been found for %jitter, and that %shimmer is higher in the older age groups (Ramig & Ringel, 1983; Biever & Bless, 1989; Orlikoff, 1990). The findings from the current study support previous research results of patterns of aging-induced changes in %shimmer by demonstrating differences in age group means as well as greater within-group variability between the older age groups (70+ and 80+) and the younger age groups. These differences were particularly evident for females after age 80.

6.2.1.2.3 SNR

The age group effect found on SNR is comparable to that described above for the other two perturbation measures, %jitter and %shimmer. When SNR was measured from the phonatory productions, vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in the four embedded vowels (except for males), SNR was found to decrease (worsen) with age for both females and males. Once again, for females SNR was significantly lower (worse) in the 80+ group than in the three other age groups. The findings in this study that show SNR lowers with age for adults are consistent with previous research where SNR was reported to be lower in elderly participants (Xue & Deliyski, 2001; Ferrand, 2002; Gorham-Rowan & Laures-Gore, 2006).

A summary of findings from this study of the age group effects on the perturbation measures %jitter, %shimmer, and SNR, shows a pattern of worsening functionality for both females and males with age. In an examination of the age group effects on perturbation measures for females for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in the four embedded vowels, a pattern emerges of significant age related differences and demonstrates the potential strength of instrumental measures to detect aging-induced perturbation changes, particularly starting for females at age 70, where greater measures of within-group variability become more apparent, to the 80+ age group where significant age differences were found. It is interesting that for all three measures, the oldest 80+ age group not only showed significant differences between the younger age groups, but also showed greater within-group variability. This suggests that for females, %jitter, %shimmer, and SNR may be considered good indicators of the elderly voice with the difference becoming most evident past age 80. In addition, as analysis results based on the vowel /a/ sustained in a one-syllable task identified more instrumental measures showing a significant aging effect than those based on the isolated vowel /a/ sustained at normal pitch alone, an increase of task variety may also assist in revealing the increase voicing variability due to aging. On the whole, perturbation measures were found to worsen as people age for more for females than males, with %jitter and %shimmer increasing and SNR decreasing.

6.2.1.3 Formant Frequencies

The following sections describe the age group effect on the acoustic variables F1 and F2 obtained from four different types of phonatory production (1) from the vowel /a/ sustained at normal pitch, (2) from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), (3) from the vowel /a/ embedded in the word “cars”, and (4) from the four vowels / i, ɔ, u, a / embedded in a sentence.

6.2.1.3.1 F1

A significant age group effects on F1 was found for both females and males measured from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), and for females when measured from the four embedded vowels, but not on F1 from the vowel /a/ sustained at normal pitch for either females or males. A common pattern observed in the above phonatory production conditions was that F1 decreased with age for females and increased with age for males.

The finding in the current study that for females F1 lowered with age was not unexpected as studies have shown that the formants do tend to lower in the elderly (Endres et al., 1971; Linville & Fisher, 1985; Linville & Rens, 2001). One explanation why formants would be expected to change with age is the interrelationship between formants and the size, shape and volume of the vocal tract. As discussed in Section 2.2.3, physiological aging causes changes to the vocal tract which could then influence formant production. Xue & Hao (2003) suggested that the lowering of formants with age might be due to a characteristic lengthening of the vocal tract in the elderly which occurs when the larynx lowers with age as the cervical muscles become more flaccid and atrophy (Luchsinger & Arnold, 1967). As well, intervertebral disks become thinner (Kahane, 1980), which may be more common in females who experience a greater loss of vertebral bone density (Linville & Rens, 2001). Additionally the shape of the oral cavity may change with loss of teeth and the introduction of dentures.

However, the findings that F1 increased for males with age are less clear. Because F1 increased for males with age across a variety of phonatory tasks, i.e., the vowel /a/ sustained in a one-syllable task (normal, high and low pitch and /m/ and /h/-initiated) and in the four embedded vowels, it means that the factor which caused F1 to increase rather than decrease with age, was independent of pitch change and/or vowel production, and was a generalized production feature. This suggests that either the combined components of the vocal tact became smaller with age, which is unlikely due to the well established descriptions of physiological aging, (although the vocal tract was not measured in this study) or that there was some articulatory strategy where the tongue was generally kept positioned lower in the mouth.

Some gender differences in the way formant frequencies change between elderly females and males were reported by Linville and Rens (2001), who found that although the formants lowered for both elderly females and males, the percentage of F1 decrease for the first three spectral peaks was greater in females (at 29%, 10% and 9%) when compared to males (at 11%, 2% and 2%). They found that peaks one and two were significantly lower for females in older groups, whereas for males, the age group effect was not as great and although the formants did lower, they weren't statistically significant and were reported as a tendency for F1 to lower with age. They speculated that there might be a "mixed model of vocal tract resonance changes with age for adults in which an interaction exists between genders, the resonance effects of laryngeal lowering, and vowel articulatory patterns" (p. 323).

Previous studies have reported that F1 lowered for both females and males with age (Endres et al., 1971; Linville & Fisher, 1985; Linville & Rens, 2001). The findings in the current study that F1 did not lower in males with age, though it did lower in females, suggests the gender differences may be due to differences in vowel articulatory patterns.

6.2.1.3.2 F2

Age group effects on F2 obtained from the vowel /a/ sustained at normal pitch were found for females where it lowered with age, and was significantly lower in the 60+ age group compared to the other three age groups. This finding agrees with previous research (described above) where the formants were found to decrease with age. However, the findings in the current study show that F2, as did F1, increased for males in the older age groups.

In this study the lowering of both F1 and F2 with age for females and not for males may be an indication of greater lengthening of the supraglottic tract in women and changes in tongue placement during vowel production in elderly males. Linville & Rens (2001) suggested that the greater degree of aging-induced formant lowering found more often in woman than in men, might be due to greater weakening of laryngeal soft tissue support (ligaments and strap muscles) in women. Another suggestion proposed by Linville and Rens (2001) to explain why formants do not lower for elderly males as much as they do for females, is that elderly men tend to centralise their tongue position during vowel production more than females which might result in "less dramatic evidence of overall formant frequency lowering in men" (p. 328).

6.2.1.3.3 Vowel Space Area

Significant age group effects on vowel space area were not found for either females or males. Significant age group effects were also not found when the data were analysed separately by New Zealand English, British English and U. S. English subgroups. When the first two formants were analysed for the four embedded vowels /i, ɔ, u, a/, significant age group effects were only found on F2 for females for the embedded vowel /a/ and not for the other three vowels /i, ɔ, u/ for either females or males. These findings suggest that, with the exception of F2 for females in the vowel /a/, since age group effects were not found for either F1 and F2 for the vowels /i, ɔ, u, a/ embedded in a sentence, then the vowel space area dependent on these vowels would not be expected to change as a function of age. The change in F2 /a/ for females was not enough to shift the vowel /a/ to produce significant vowel space area age effects.

6.2.1.4 VOT

Voice onset time was measured in this study from /ka/ in the word ‘car’ and from /tu/ in the word “two” extracted from the test sentence “We saw two cars.” It requires fine articulatory and laryngeal motor coordination to accomplish the smooth transition from unvoiced articulation to voiced phonation; controls that may be affected by normal aging, and from which one might expect to see greater variability. In the current study significant age group effects were found on VOT (/ka/) for females and on /ka/ and /tu/ for males although with different patterns of aging-induced change for each gender. VOT increased overall with age for women and was generally longer in the three older female age groups than in the youngest age group. On the other hand, for males, VOT for both /ka/ and /tu/ decreased (became shorter) consistently with age, and with the greatest differences found between the youngest 35+ age groups and the 80+ age groups.

Voice onset time has generally been reported in the literature to be longer in females than in males. In the current study VOT (/ka/) was longer for females and shorter for males. These findings compare favorably with other studies of VOT that measured gender differences in different age populations. Voice onset time was reported to be longer for females and shorter for males when measured in groups of elderly participants (Sweeting & Baken, 1982; Torre III & Barlow, 2009), and in groups of younger participants (Ryalls et al., 1997; Robb et al., 2005). The fact that similar gender differences in VOT have been found in both young an old populations, the differences might be, according to Torre III & Barlow (2009), "attributed to anatomical differences between men and women generally" (p.326). This would suggest that although aging patterns on VOT would certainly be influenced by the natural course of physiological neuromuscular aging, it might also be controlled to some extent by anatomical differences.

In the current study VOT (/ka/) increased with age for females and decreased with age for males; VOT (/tu/) also decreased with age for males. Similar findings on the effect of aging on VOT have been reported by Torre III and Barlow (2009), who found that VOT was longer for /k/ for older females and shorter for older males compared with younger groups. Aging differences in VOT were also reported by Decoster & Debruyne (2000), though the direction of change was different. They found that VOT increased strongly with age from voice samples of connected speech from 20 male Dutch professional newsreaders recorded three decades apart. The difference in results between the current study and the one by Decoster & Debruyne (2000) could be explained in part by differences in methodology. In the Decoster & Debruyne (2000) study the participants were reporters from the national radio service and their speaking style was described as being of a ‘professional standard’. Moreover, their analysis was done from running speech rather than from the individually spoken sentences used in the current study. Sweeting & Baken (1982) found no significant age differences in VOT in three age groups between 25 and 91.

Changes in the rate of speech as a function of age may have contributed to the aging differences found in VOT. Speaking rate is reported to be a strong predictor of VOT, where slower talkers produced the longer VOTs (Allen, Miller & DeSteno (2003). As a slower speaking rate is one of the recognised characteristics of elderly speech (Smith et al., 1987; Brown et al., 1989; Shipp et al., 1992), it would not be unexpected to see its effect on VOT since slower rates of speech have also been associated with longer VOT duration for voiceless stops (Port & Rotunno, 1979). Significant age group effects on sentence length were not found in the current study (see Section 6.2.1.5), however, mean sentence length did increase for females and decrease males with age, and having perhaps some influence on VOT; this would need to be confirmed with further investigation.

6.2.1.5 Sentence and Vowel Durations

Sentence duration was measured from the sentence “We saw two cars.” spoken in both a normal and open jaw posture; vowel duration times were obtained from the vowels embedded in the same sentence. In the current study, no significant age group effects on either sentence or vowel duration times were found for either females or males. On initial examination, this finding failed to support studies which show that speaking rate tends to slow with age or recognize slow speaking rate as one of the characteristics of the elderly voice (Smith et a., 1987; Brown et al., 1989; Linville et al., 1989). One possible explanation for this conflicting result lies in the differences in both the nature and in the length of the speaking materials measured in this study. In the current study, a short sentence of four one-syllable words was used, whereas in other studies speaking rate was measured from longer and more varied speaking materials, such as selected sentences and paragraphs from the Rainbow Passage (Brown et al, 1987; Shipp et al., 1992; Linville et al., 1989). The duration times of the four word sentence used in this study might have been too short to identify the age group effect on speaking rate.

6.2.1.6 H1 – H2 Amplitude Difference

The H1-H2 amplitude difference was obtained by calculating the difference, measured in decibels, between the first (F0 = H1) and second (H2) harmonics from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). In the current study significant age group effects on the H1-H2 amplitude difference for the vowel /a/ sustained at normal pitch were not found for either females or males. However, for vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), significant age group effects were found on the H1-H2 amplitude difference for both females and males. For females, H1-H2 amplitude difference was higher in the three oldest age groups and was significantly higher in the 70+ age group. Post hoc testing revealed that the aging pattern for males was not as straight-forward. The H1-H2 amplitude difference was significantly higher in the 35+ and 80+ age groups, and then decreased significantly for the 60+ and 70+ age groups.

In an investigation of aging effects on F0 amplitude, Linville (2002) found F0 amplitude increased significantly for elderly females and showed an increasing trend for elderly males. A higher or more dominant fundamental amplitude would contribute to calculated higher H1-H2 amplitude differences. Two possible consequences of an increase in F0 amplitude are one, that it could contribute to higher H1-H2 amplitude differences which are associated with subjective measures of greater breathiness in vowels, and secondly, increases in F0 amplitude have been attributed to increases in OQ (Klatt & Klatt, 1990). An increase in OQ, i.e., the longer time the vocal folds are open within each vibrating cycle, would contribute to a breathier voice. In a study that compared the flow glottograms of different voice qualities, breathy voices were found to show higher wave amplitudes than either pressed or normal voices (Gauffen & Sundberg, 1989), and with a greater F0 amplitude which "is dependent on the shape and amplitude of the flow pulse" (Sundberg & Hogset, 2001, p. 28).

Increased breathiness one of the well reported characteristics of elderly speech (Ryan & Burke, 1974; Hartman & Danhauer, 1976; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006). The significantly higher H1-H2 amplitude differences found in the current study for older females may provide an explantion for the increases in breathiness found with age. Age effects on the H1-H2 difference were detected through measurement of the five task vowel /a/ sustained in a one-syllable production and not on the sustained isolated vowel /a/, suggesting that identifying aging effects may lie in greater task variation (pitch and CV context, in the current study).

6.2.2 Aerophone Findings

The following sections describe the age group effects on measures obtained using the Aerophone II system, including measures of SPL and MFR, which were measured from a sustained vowel, and measures of air pressure, air flow rate, and LAR, which were obtained from the sequential /pa/ production.

6.2.2.1 SPL

Sound pressure level was calculated from the vowel /a/ sustained for 2 to 3 seconds in normal pitch through a facemask. Significant age group effects were not found for either females or males, although examination of the data does show an aging pattern for SPL for females where it decreased from the youngest to oldest age groups. The aging pattern for males was less clear. The fact that lower SPLs did not reach statistical significance for age is surprising since a low SPL has often been observed as a feature of the elderly voice and differences in SPL between young and elderly groups have been widely reported in the literature (Ptacek et al., 1966a; Linville, 1996; Baker et al., 2001; Hodge et al., 2001).

Two critical factors that control SPL are air pressure and airflow. In the current study (described below in section 6.2.2.2) age group effects were not found for airflow, air pressure or laryngeal resistance (the ratio of air pressure to airflow). One possibility aging effects were not found in the current study is the smaller age range of the participants. In previous studies where aging effect in SPL were found, groups with large age differences were compared, e.g., Hodge et al. (2001) compared a group of young males mean age = 30 and a group of older males mean age =77; Baker et al. (2002) studied a group of young adults, with an age range of 26-28, and an older adults, age range 68 – 70). The pattern of age related changes between age 60 and 93 in the current study, might not have been great enough to identify significant differences.

Another factor that could have influenced SPL in the current study was the use of a facemask while participants phonated the sustained vowel /a/ in normal pitch. Sound pressure level is associated with the degree of jaw opening (Schulman, 1989; Dromey &

Ramig, 1998; Huber & Chandrasekaran, 2006) and although the size of the facemask allowed for ample jaw movement, the participants may have felt that the presence of mask itself posed restrictions on jaw movement. However, we do know that the size of the mask was large enough to allow for a wide range of jaw movements because when the participants were asked to speak in an open jaw posture with the mask in place, significant posture effects were found (See Section 6.3.2.1).

6.2.2.2 Airflow and Air Pressure

In the current study, age group effects were not found on any of the aerophone measures, MFR, air pressure, air flow rate or laryngeal resistance for either females or males. The literature on studies that examined age group effects on aerodynamic characteristics, report mixed findings both for age group effects and for age by gender effects, showing either no significant age group effects or differing results. There have been reports in the literature of greater intersubject variability in the aerodynamic measures of older individuals (Biever & Bless, 1989; Sapienza & Dutka, 1996; Hoit & Hixon, 1992). This variation may be a consequence of differences in aging-induced anatomical, histological and physiological changes, the patterns of which are not necessarily related to chronological age (Ramig & Ringel, 1983; Sataloff et al., 1997; Mathieson, 2001). The differences in physical aging patterns along with greater variability may be responsible for the mixed findings reported for aerodynamic measures. In the present study, the finding that aerodynamic measures failed to reveal a significant age group effect may be related to the high within-group intersubject variability.

It had been suggested in the literature that where age group effects were not found, compensatory laryngeal behaviours might have masked the characteristics of the aging larynx. For example, the absence of age group effects on airflow measures in healthy older females was seen by Sapienza & Dutka (1996) as being due to the fact that the “assumed anatomical changes produce less significant phonatory change in the healthy individual or the healthy individual is more capable of using strategies to counteract degenerative laryngeal changes” (p. 322). Similarly, Hoit, and Hixon (1992) also attributed the absence of age group effects, in their study of geriatric females, to “behavioral adjustment to counteract the effects of age-altered laryngeal structures” (p. 311).

The present findings that there were no significant age group effects on MFR for females and a trend for the MFR to become variable in the older age groups agree with previous studies that have also failed to show significant age group effects on the measure of airflow rate for females but have shown greater variability in airflow rates in older females compared to younger females (Biever & Bless, 1989; Sapienza & Dutka, 1996). In this study, age group effects on air pressure were not found for either females or males. Reports on age group effects on air pressure have shown disparate results where findings have ranged from evidence of reduced air pressure in the elderly (Ptacek et al., 1966a), reports of no differences between younger and older populations (Melcon et al., 1989; Baker et al., 2001), report of greater air pressure in elderly males (Higgins & Saxman, 1991), to findings that show age differences in air pressure for females (Hoit & Hixon, 1992). The mixed outcomes from studies on aerodynamic measures of the elderly may be indicative of the importance the combination of the extent to which the larynx has aged, along with any compensatory behaviours employed.

6.2.3 EGG Findings

Electroglottographic measurements were obtained from the first derivative of L_x waveform recorded from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the four embedded vowels in the sentence "We saw two cars." produced in normal pitch.

6.2.3.1 SQ

An age group effect on SQ was found for females and males where it increased with age in the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in the four embedded vowels. In a study that only looked at males, Murty et al. (1991) reported the older male group had higher SQs than the younger group. Because higher SQs are associated with longer opening phases, the increase in SQ in the elderly may be due to the effects of aging-induced physiological changes to the larynx as described in Section 2.2.2 Laryngeal Changes, resulting in a slowing in vocal fold opening.

The fact that in the current study, SQ was higher in the older age groups for females and for males in both the one-syllable tasks and the embedded vowels, suggests that aging might not only have the overall effect of slowing vocal fold movement, but that this slower movement is consistent through a variety of phonatory tasks, e.g., changes in pitch and vowel articulatory movements.

6.2.3.2 OQ

In the current study, an age group effect on OQ was found where it decreased for females, and increased for males from age 60+, from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the four embedded vowels. These findings agree with Higgins & Saxman (1991) who reported that in sustained phonation OQ decreased with age for females and increased with age for males. Winkler & Sendlmeier (2005) also found that OQ increased with age for males but found no significant differences in OQ between young and older females.

Higher OQs indicate that the vocal folds are open longer during each vocal cycle, which therefore allows more air to pass through the glottis. An increase of air through the glottis may affect vocal quality and listener perception of age. Winkler & Sendlmeier (2005) found that the higher OQs in older males were related to increases in breathiness which 'may contribute to the listener's perception of increased age' (p. 213).

The different aging patterns in OQ for females and males found in the current study, as well as findings from other studies (Higgins & Saxman, 1991; Winkler & Sendlmeier, 2005) may be a consequence of the overall changes that occur to the laryngeal structure as a result of physiological aging, and include as well, changes with respect to gender differences described in Section 2.2.2 Laryngeal Changes

The outcomes from the current study suggest that instrumental measures of OQ may be useful in identifying aging patterns in vocal fold movement insofar as OQ is concerned where data have generally shown that it decreases in females and increases in males. An increase in OQ in males may be seen as increased breathiness, one of the salient feature of the elderly voice. Open quotient values may affect perceptual age judgements in both genders, as OQ increased, the judged age of the speaker also increased (Winkler & Sendlmeier (2005).

6.3 Open Jaw Posture Effect on the Aging Voice

One of the objectives of this study was to investigate the effect an open jaw posture has on acoustic measures in the population of aging healthy adults. Phonatory strategies that can demonstrate improved phonatory outcomes, such as an open jaw posture, would be helpful in clinical programs managing voice disorders in the elderly. With the recognized growth of the aging population comes the increased need, along with patient expectation, for age-appropriate voice therapy.

6.3.1 Acoustic Findings

Overall results for the vowel /a/ sustained at normal pitch, found that when participants were asked to 'speak with an open jaw' they increased the extent of jaw opening by up to 55.7mm. An open jaw posture generally had the effect of increasing pitch, sound pressure level, subglottal pressure, mean flow rate and vowel space area. Results for both females and males revealed significant open jaw posture effects on F0, F2, VOT (/ka/), MFR, SPL and vowel space area. In addition for females, significant posture effects were found on F1, subglottal pressure and the H1-H2 amplitude difference, and for males, significant posture effects were found on %jitter and VOT-/tu/. Fewer significant posture effects were found for the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), F0 and H1-H2 amplitude differences for females and males, and F2 for females, revealing perhaps that posture has less of an effect on pitch or on the vowel /a/ preceded by a consonant. Results from embedded vowels in running speech showed posture effects across a number of variables including F0, %jitter, %shimmer, SNR for both females and males and F1 for males.

6.3.1.1 F0

In the current study, in an open jaw posture F0 increased for both females and males in each of the phonatory productions measures, i.e., the vowel /a/ sustained at normal pitch, the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and the four embedded vowels. Studies that have examined the effect of jaw opening on F0, have also shown that increases in F0 are related to increases in the extent of jaw opening (Austin, 2007; Sundberg, 2009). Although similar results were found, the participants in these studies differed from those in the current study in their use of professional opera singers who employed a ‘wider jaw strategy’ in an attempt to raise F0 above F1 while singing, whereas the participants in the current study were not trained singers, did not phonate in a singing mode and were older.

An important outcome of an increase in F0 as a result of an open jaw posture was seen in its effects on phonatory stability for both females and males (see Section 6.3.1.2) and in the H1-H2 amplitude difference for females (sees Section 6.3.1.6). A higher F0 as a result of jaw lowering, may also prove beneficial to elderly females for whom pitch generally lowers with age (Hartman & Danhauer, 1976; Linville, 1996; Gorham-Rowan & Laures-Gore, 2006) and would prove valuable in countering some of the troublesome, more masculine perceptions of the elderly female voice.

6.3.1.2 Phonatory Stability

The acoustic measures %jitter, %shimmer, and SNR, referred to collectively as measures of phonatory stability, were obtained from the vowel /a/ sustained at normal pitch, the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in the four embedded vowels /i, ɔ, u, a/. These three acoustic measures describe the stability of the acoustic signal in terms of its cycle to cycle frequency variation, cycle to cycle amplitude variation and the ratio of the acoustic signal to noise. Significant open jaw posture effects were found only for %jitter in males. In general, in the three older male age groups, although a posture effect was only found significant for %jitter, all three measures of phonatory stability showed some improvement in an open jaw posture, i.e., %jitter and %shimmer decreased and SNR increased.

It had been hypothesised at the beginning of this study that an open jaw posture would result in improved measures of phonatory stability. This was based on research that found jaw widening improved approximation of the vocal folds (Boone, 1997) and promoted better vocal fold adduction (Cookman & Verdolini, 1999). In the current study although the only significant posture effect on %jitter was found for males, there was a tendency for %jitter and %shimmer to decrease (improve) and for SNR to increase (improve) in an open jaw posture, though these factors were not found to be statistically significant. The improvements in %jitter, %shimmer and SNR might be explained by a concomitant increase in SPL in an open jaw posture. Brockman, Storck, Carding, & Drinnan (2008) found that for healthy adults, when SPL was lower, %jitter and %shimmer increased. In the current study SPL increased significantly in an open jaw posture for both females and males suggesting a positive association between higher SPLs and improvements in measures of phonatory stability.

As described in Section 6.3.1.1, in the current study F0 was found to increase significantly in an open jaw posture for both females and males and might have an indirect impact on phonatory stability. Higher pitch has been shown in this study to produce a positive effect on measures of phonatory stability. Percent jitter, %shimmer and SNR were all found to improve for both females and males when the vowel /a/ was phonated in high-pitch, i.e., %jitter and %shimmer were lower in high-pitch, and SNR was higher in high-pitch, than in the normal-pitch, low-pitch, /ma/ or /ha/ in normal pitch condition. When the vowel /a/ was phonated in low-pitch, the opposite effect was observed; measures of phonatory stability worsened. From the findings in this study, the use of an open jaw posture to increase F0 may in fact contribute to better measures of phonatory stability.

Voice quality characteristic of harshness and hoarseness are well recognised features of the elderly male voice (Hartman, 1979) and increases in these two features of voice quality may be due to higher levels of jitter and shimmer (Linville, 1996). The findings that an increase in jaw widening for males has a significant effect on lowering mean %jitter values, suggests it could be helpful in reducing vocal harshness/hoarseness and help support in communicating a more favourable impression of an elder person's voice.

6.3.1.3 Formant Frequencies

The significant increase on F1 for the isolated vowel /a/ sustained at normal pitch in an open jaw posture found for females was not unexpected since it is well documented that F1 is inversely related to tongue height, i.e., the lower the tongue the higher F1 (Lindblom & Sundberg, 1971), and that as jaw opening widens, tongue position is naturally lowered. For males however, despite also using an open jaw posture, F1 didn't increase as expected and even slightly decreased from normal posture to open jaw posture. One reason for the downward shift in F1 for males in the current study may be that the magnitude of jaw widening was less in males.

The increase in F1 for females as a result of jaw opening may benefit the speaker since the value of F1 has been shown to be an important perceptual clue to speaker age. Linville & Fisher (1985) found that F1 was a powerful discriminator of actual age in three groups of young, middle-age and old women. When F1 was lower in whispered vowels, speakers were judged as being older. The increase found in F1 in an open jaw posture for females may contribute beneficially to the perception of a younger sounding voice.

Formant two significantly decreased in an open jaw posture for both females and males. These findings corroborate those of Lindblom & Sundberg (1971) who found that as jaw opening widens, greater pharyngeal constriction is produced and F2 would therefore decrease as a function of jaw opening. Huber et al., (1999) also found that F2 decreased as jaw opening widened and that this was a due to increased intensity.

The results from this study from the isolated vowel /a/ sustained at normal pitch, show that F1 increases in females, and F2 decreases in both females and males in an open jaw posture. An important implication of the shift in formant values for corner vowels is its effects on vowel space area. The movement of a corner vowel such as /a/, where F1 increases and F2 decreases, promotes an expansion of vowel space area, and greater vowel space area has been associated with better differentiation between vowels and therefore higher speech intelligibility (Bond & Moore, 1994; Bradlow et al., 1996). The posture effect on F1 and F2 for the four embedded vowels, /i, ɔ, u and a/ and the subsequent effects on vowel space area as a function of an open jaw posture are discussed in the Section 6.3.1.4.

6.3.1.4 Vowel Space Area

To investigate the effect of jaw posture on speech intelligibility, vowel space area was calculated using as coordinates the F1 and F2 Hz frequencies of the vowels /i/, /ɔ/, /u/ and /a/ from the test sentence “We saw two cars.” spoken using normal pitch in both a normal and an open jaw posture. The cumulative effect of the changes to F1 and F2 between a normal and an open jaw posture was an overall expansion of the vowel space area for both females and males, as seen in the movement of each of the four vowels away from a more central position. The increase in vowel space area in an open jaw posture was found to be statistically significant for both females and males.

When the posture effects of jaw movement, i.e., from normal to open jaw, on F1 and F2 are evaluated separately for each of the four embedded vowels, the particular pattern of change for each vowel shows a direction of movement further from a centroid position. The combination of the changes to F1 and F2, either by increasing or by decreasing in value, defines the shift in vowel placement. For females for example, when jaw posture changed from normal to open jaw, in the vowel /a/ F1 increased and F2 decreased, in the vowel /u/, both F1 and F2 decreased, in the vowel /i/ F1 decreased and F2 increased and in the vowel /ɔ/ F1 increased and F2 decreased. The net effect of these changes was to produce a greater distance of the vowels from each other. For males, the net effect of vowel movement due to formant shifts as a result of an open jaw posture was similar to that found for females. The changes in F1 and F2 from normal to an open jaw posture that ultimately increased vowel space area, suggests greater tongue movement both in its height and in its front and backward movements.

To further examine the effect of jaw posture on vowel space area, the vowel space areas from three subgroups of English language speakers (speakers of New Zealand English, British English and U.S. English) were analysed. Vowel space area was also found to increase in the three subgroups in an open jaw posture. Statistically significant posture effects were found for the New Zealand and British English speakers, the small sample size, particularly in the British English speakers should be noted (see Appendix 14).

The findings of this study demonstrate that vowel space area increases in an open jaw posture and suggest that this increase occurs in English language speakers as a group as well as in subgroups of English language speakers. However, the magnitude of vowel space expansion and the findings of significant posture effects on vowel space area in an open jaw posture appear to differ with speakers of different English accents.

Previous research has reported that slower speaking rates contribute to vowel space area expansion (Moon & Lindblom, 1994; Turner et al., 1995; Tjaden & Wilding, 2004). At slower rates of speech, orofacial velocities (of upper and lower lips, jaw and tongue) decrease (McClean, 2000) which would consequently allow more time for the tongue to reach the more extreme vowel target areas. In order to investigate rate of speech and vowel space area, the duration times of the test sentence and the embedded vowels spoken in normal posture and in an open jaw posture were measured. In the current study, durations of vowels embedded in a sentence and sentence durations were all found to be significantly longer in an open jaw posture for both females and males. The longer vowel duration times, during production in an open jaw posture, would allow more time for articulatory movements to achieve greater precision, as well as for achieving better vocal control of oral-laryngeal coordination, resulting in better vowel differentiation.

The importance of the finding that vowel space area increases in an open jaw posture, is that larger vowel space areas have been associated with better differentiation between vowels and thus higher speech intelligibility (Bradlow et al., 1996; Weismer et al., 2001; Liu, et al., 2005). The findings in the current study of elderly speakers that vowel space area increases in an open jaw have important implications for improved speech intelligibility for this demographic group.

The outcomes of this study have demonstrated that when jaw opening widens, vowel space area increases, suggesting improved speech intelligibility. To assess whether the increase in vowel space area as a result of greater jaw opening can be perceived by listeners as having greater speech intelligibility, a separate perceptual study was conducted to measure listeners' ability to identify vowels and to judge vowel clarity produced in two speaking conditions, normal and open jaw (see Chapter 7. Follow-up Perceptual Study). To this purpose, 40 listeners between the ages 18 and 50 from the University of Canterbury were recruited to participate in two separate tasks. Their first task was to listen to randomly presented individual vowels /i, ɔ, u, a/ in normal and open jaw posture in two different vowel length formats (fixed length, fixed length normalised to 65dB and a repeat of the fixed length sequence) and identify the vowel they heard. Secondly, they listened to vowel pairs (the same vowel spoken by the same speaker in normal posture and in open jaw posture) in three different formats (fixed length, variable length and fixed length normalised to 65dB), and were asked to judge which token in each vowel pair sounded clearer.

6.3.1.5 VOT

Voice onset time was measured from /ka/ in the word "cars" and from the word "two" (/tu/) from the four word sentence "We saw two cars." spoken using normal pitch in both normal and open jaw posture. In an open jaw posture VOT (/ka/) increased significantly for both females and males, and VOT-/tu/ increased significantly for males. Voice onset time also increased in open jaw in females for /tu/, but it did not reach statistical significance. VOT increased in an open jaw posture across both genders, in both high and low back vowels, and as well, in both front (/t/) and back /k/) voiceless plosive consonants. Because in an open jaw effect, VOT increased in different vowels (/a/ and /u/) preceded by different consonants (/k/ and /t/), it suggests that with changes in jaw posture the increase in VOT may be less dependent on a particular vowel or a particular consonant articulation position, but may instead be related to rate of speech (vowel and/or sentence length), which were found to increase significantly in an open jaw posture.

In the current study, a statistically significant increase was found for both vowel and sentence length in an open jaw posture. The effect of this increase in vowel and sentence phonation times would be a slower rate of speech. Speaking rate has been shown to be an important factor in VOT production. Slower rates of speech have been shown to produce longer VOTs (Kessinger & Blumstein 1998; Morris et al. 2008). In addition, speaking rate has also been reported to be a strong predictor of VOT, where slower talkers produced the longer VOTs (Allen et al., 2003).

6.3.1.6 H1–H2 Amplitude Difference

In the current study, significant posture effects on H1-H2 amplitude difference were found for females in an open jaw posture where it decreased for the isolated vowel /a/

sustained at normal pitch and also for females and males in the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated). Because H1-H2 amplitude difference is closely tied to subjective measures of breathiness in vowels (Klatt & Klatt, 1990) and greater H1-H2 amplitude difference are perceived as an acoustically thinner or breathier sounding voice, the findings here that it decreased in an open jaw posture suggests that an open jaw posture may help to reduce these qualities in the geriatric voice. A less breathy voice in an open jaw posture may be indicative of better vocal fold adduction or lower OQ. Evidence has shown that an open jaw posture may contribute to improved approximation of the vocal folds (Boone, 1997) and to an increase in vocal fold adduction (Cookman & Verdolini, 1999).

It was also found in this study that for both females and males the H1-H2 amplitude difference was lowest in the high-pitch phonation condition. As discussed earlier (see Section 6.3.1.1), F0 was found to increase with an open jaw posture for both genders in all phonatory conditions. The findings that in an open jaw posture F0 increases, and that this increase in pitch may have a positive follow-on effect of reducing H1-H2 amplitude difference thereby contributing to a less breathy voice or one produced with thicker vocal folds, could prove beneficial to elderly speakers.

6.3.2 Aerophone Findings

This section discusses the posture effect on measures of SPL and MFR, which were obtained from a sustained vowel and that on measures of air pressure, air flow rate, and LAR, which were obtained from the sequential /pa/ production.

6.3.2.1 SPL

Sound pressure level increased significantly in an open jaw posture for both females and males and was also higher in an open jaw posture for both genders in all age groups. An increase in SPL is particularly important for the elderly, for whom reduced loudness is one of the characteristic features of the geriatric voice (Ptacek et al., 1966a; Linville, 1996; Baker et al., 2001; Hodge et al., 2001).

The findings in the current study that jaw widening results in an increase of SPL in the geriatric population, agree with studies performed on young healthy adults where increases in jaw opening were associated with increases in intensity (Schulman, 1989; Dromey & Ramig, 1998; Huber & Chandrasekaran, 2006). In the current study the estimated subglottal air pressure increased for females and airflow rates increased for females and males in an open jaw posture. An increase in subglottic pressure is needed to increase in the intensity of the acoustic wave (Schulman, 1989) where it may cause the vocal folds to come back together faster 'creating a sharper flow shutoff corner near the baseline, raising the overall spectrum of the overtones' (p.177) (Scherer, 2006). An additional factor that may have contributed to the increase in SPL, is the more open vocal tract created when the jaw is lowered. In order to increase in SPL, along with a strong wave source, there is a requirement for 'a more open vocal tract to allow more acoustic energy to be radiated' (p. 1015) (Dromey & Ramig, 1998).

6.3.2.2 Airflow

Mean airflow rate increased significantly in an open jaw posture for both females and males. The increase in MFR may be due to an increase in respiratory driving pressure, which itself would be a consequence of greater vocal fold adduction. Evidence of better vocal fold adduction in an open jaw posture is inferred in the current study from significant increases for both females and males in SPL (intensity) in the sustained isolated vowel /a/ and in F0 (pitch) in the sustained isolated vowel /a/ and in the embedded vowels produced in an open jaw posture, both of which are dependent upon increases in subglottal air pressure. Subglottal air pressure increases as vocal fold adduction increases, and in the current study, estimated subglottal pressure increased in an open jaw posture for both females and males, although it was only statistically significant for females. Participants were asked to maintain normal pitch and intensity, so the increases in SPL and F0 could be accounted for by better vocal fold adduction as a result of an increase in open jaw posture.

The findings for MFR showed males generally showed higher airflow rates than females in both normal and open jaw posture, and that the increase in MFR in an open jaw posture was also greater in males than in females. Higher airflow rate in males than females may be explained by differences between males and females in the time in life when glottal gaps are generally first known to appear. Females normally experience glottal gaps from an early age (Biever & Bless, 1989; Linville, 1992) where compensatory strategies to support better laryngeal valving may be developed over time. However, for males, because the appearance of glottal gaps may occur later in life, as a result of atrophy to the internal laryngeal muscles (Luchsinger & Arnold, 1967; Honjo & Isshiki, 1980), the greater MFRs measured in this study may be attributable to the less developed skills in males to compensate for reductions in vocal fold adduction.

6.3.2.3 Air Pressure

Air pressure increased significantly in an open jaw posture for females, and it also increased in an open jaw posture for both genders in all age groups (though not significant). The increase in air pressure could be explained by better vocal fold adduction resulting from an open jaw posture, since a lowered jaw has been shown to support better vocal fold approximation and an increase in vocal fold adduction (Boone & McFarlane, 1993; Colton & Casper, 1996; Boone, 1997; Cookman & Verdolini, 1999). The increase in air pressure in an open jaw posture reported here is important, as adequate levels of air pressure, specifically subglottic pressure, are needed to set the vocal folds into vibration and sustain phonation. In addition, because air pressure is one of the two critical factors used to calculate laryngeal airway resistance (the other being airflow), an increase in air pressure may translate into increased laryngeal airway resistance with an associated increase in SPL. This would be particularly beneficial to the elderly population where reduced SPL is a commonly identified feature of the geriatric voice.

6.3.3 EGG Findings

The following sections describe the posture effects on the two EGG measures, SQ and OQ measures, which were obtained from the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and from the embedded vowels /i, ɔ, u, a/.

6.3.3.1 SQ

Statistically significant posture effects were not found on speed quotient in either the isolated vowel /a/ sustained at normal pitch or the embedded vowels /i, ɔ, u, a/. However, for females it was found that when SQ decreased in an open jaw posture, the increase of fundamental frequency, due to open jaw posture, was even higher. As speed quotient is the ratio between the opening phase and closing phase, a lower SQ indicates a shorter vocal fold opening time; possibly due to a more relaxed laryngeal musculature. This finding suggests that if an open jaw approach could induce a greater degree of relaxation of the laryngeal musculature, the effect of an open jaw posture in raising pitch would be enhanced.

6.3.3.2 OQ

Open Quotient was found to be significantly higher in an open jaw posture for females when measured from the isolated vowel /a/ sustained at normal pitch, indicating that the vocal folds were open longer, as a percentage of the full glottal cycle. The finding that OQ increased for females in an open jaw posture is surprising, because SPL was also found to increase significantly in an open jaw posture for females and 'OQ is generally felt to decrease with increases in vocal intensity' (Hodge et al., 2001), (p. 502). One consequence of a longer OQ is increased airflow. In the current study, along with an increase in OQ, MFR was also found to be higher in an open jaw posture reflecting the longer time the vocal folds were open.

6.4 Sustained Versus Embedded Vowels

In the current study, two sets of acoustic data were recorded, namely, the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and the four vowels /i, ɔ, u, a/ embedded in a sentence. Both data sets were subject to an analysis of age and jaw posture effects for the acoustic variables F0, %jitter, %shimmer, SNR, F1 and F2. The aging factor was analysed to identify if phonatory behaviours are affected by the normal aging process. Analysis of the jaw posture factor examined what effect, if any, jaw posture has on the phonatory behaviours of healthy adults. The findings show that the effect of age and jaw posture on phonatory variables identified in these two data sets are generally in agreement with only minor differences. With the isolated vowel /a/ sustained at normal pitch, the age group effect was found to be more evident for females. In addition, F1, H1-H2 amplitude difference, SQ, and OQ were not found to be sensitive to the aging effect if the test is limited to the isolated vowel /a/ sustained at normal pitch, suggesting that an increase in task variety may be useful to increase the discriminatory power of the instrumental measures.

Of all the variables measured, F0 appears to be the one most highly sensitive to changes along the aging continuum, as well as to changes in jaw posture. For F0, significant age and posture effects were found for both genders in every phonatory condition, i.e., in the five tasks as a group and in the individual tasks (the vowel /a/ in normal-pitch, low-pitch, high-pitch, /ma/ and /ha/) as well as in the four embedded vowels as a group and in the individual vowels (/i, ɔ, u, a/). The well reported physiological changes to the vocal folds that occur as people age may be responsible for the observed decrease in F0 with age for females and for the increase in F0 for males in each of the testing conditions. The finding that F0 increases consistently in an open jaw posture for both females and males may be related to the effect of laryngeal positioning, which can be affected by jaw posture, on vocal fold tension. During vowel phonation in an open jaw posture, the cricothyroid muscle is contracting, tilting the thyroid cartilage forward thereby elongating the thryoarytenoid muscle and increasing F0. An open jaw posture appears to be an effective strategy to increase F0 without imposing excessive head and neck muscle tension in all adult age groups.

Chapter 7. FOLLOW-UP PERCEPTUAL STUDY

The purpose of the follow-up perceptual study was to determine whether the voice improvement induced by an "open jaw" posture as observed through the acoustic and physiological measures in this study could be perceived by listeners. The rationale, hypotheses, methodology, results, and discussion for this follow-up perceptual study are described in this chapter.

7.1 Rationale and Hypotheses

In the main research study, described above, acoustic measures were used to compare the voice of healthy adults by age group (35+, 60+, 70+, and 80+) and jaw posture (normal and open jaw). One of the hypotheses proposed was that an open jaw posture would change the formant frequencies in the direction toward better vowel differentiation due to less constrained tongue movement. It was postulated that the effect of such adjustments to jaw posture on articulatory movements and vocal tract resonance would be observable from changes to F1 and F2. To this purpose, we have plotted the quadrilateral vowel space, with the F1 and F2 frequencies shown on the x- and y-axes in a plane Cartesian coordinate system, using measures taken from four corner vowels, /i, ɔ, u, a/ which were segmented out from the test sentence, "We saw two cars.", produced in two jaw postures for comparison. As discussed in Section 6.3.1.4, the vowel space area was indeed found to increase for both females and males when produced in an open jaw posture as compared with a normal jaw posture. The importance of these findings in its relationship to speech intelligibility is that a larger vowel space area has been associated with a higher degree of speech intelligibility (Bradlow et al., 1996; Weismer et al., 2001;

Liu et al., 2005). Therefore, if an open jaw posture has the effect of improving speech intelligibility in the elderly by resulting in clearer vowels, we would then clearly be in a position to propose that such facilitated movements might be incorporated into voice and speech therapeutic programs. However, before such suggestions can be put forward, it would be prudent to determine if the acoustic changes found to be associated with an "open jaw" posture could translate into improved speech clarity as judged by listeners.

The main purpose for conducting the follow-up perceptual study is to ascertain whether the vowel space expansion resulted from an "open jaw" posture, as found in the current study, was indeed an indication that the vowels produced in an "open jaw" posture would be easier to identify in terms of vowel intelligibility as compared with those produced in a normal jaw posture. Based on the relationship established in the literature for vowel space and speech intelligibility, it is hypothesised that the vowel identity of vowels produced in an "open jaw" posture would be correctly identified by listeners more often than those produced in a "normal" jaw posture. In addition, based on the present finding of a positive effect of an "open jaw" posture on the acoustic measures related to voice quality, it is also hypothesized that vowels produced in an "open jaw" posture would be judged as "clearer" than those produced in a normal jaw posture.

7.2 Methodology

Details of the follow-up perceptual study are provided as follows, including participants, participant's task, stimuli, instrumentation, procedures, measurement, data analysis, and statistical analysis.

7.2.1 Participants

A quota sampling strategy was used to recruit normal hearing listeners for the perceptual study. Forty participants, including 20 females (age range 18-42, mean = 25.3 years, SD = 7.9) and 20 males (age range 18-47, mean = 23.6 years, SD = 6.7), were recruited from the student population of the University of Canterbury (Christchurch, New Zealand) through posted signs and personal contacts. The subject inclusion criteria included normal hearing as confirmed by an audiologist on the day of the experiment through a hearing screening test and aged between 18-50 years. In addition, in order to have a homogeneous group of native New Zealand English speaking listeners, listeners had to have New Zealand English as the first language, and having lived in New Zealand until age seven before moving aboard or moved to New Zealand before age seven. The cut-off point for acquiring native-like proficiency in a second language is around the ages 6 and 7 (Hyltenstam, 1992).

Volunteers were presented with an information sheet describing the project and the required tasks (see Appendix 25) and were compensated for their time with a petrol voucher to the value of 10 New Zealand dollars. After signing a form agreeing to participate in the study (see Appendix 26), each listener completed a personal background form that asked for details about aspects of the participant's language-related history (see Appendix 27). All forms and advertisements used in this study were approved by the Human Ethics Committee of the University of Canterbury, Christchurch, New Zealand. A hearing screening test at 25dB for 500Hz, 20dB for 1000Hz, 2000Hz, 4000Hz and 8000Hz was administered by an audiologist to each participant to ensure normal hearing levels. Volunteers with a hearing loss were excluded from the study and informed about the hearing test results and further contact information needed for professional hearing services.

7.2.2 Participants' Tasks

The participant was asked to perform two listening tasks, namely, vowel identification and vowel clarity tasks. In each trial for the vowel identification task, the participant was presented with a single vowel, 100 ms in length, and asked to indicate which vowel they thought they heard by selecting one of the five vowels shown on the computer screen (see Appendix 28). The five screen choices were /ee/ as in "bee", /eh/ as in "bet", /a/ as in "pa", /aw/ as in "paw", and /u/ as in "boot". The participants were not provided with any information about the age or gender of the speakers.

In each trial for the vowel clarity task, the participant was presented with a contrast pair, each consisting of one vowel produced in a normal posture and the same vowel produced by the same speaker in an open jaw posture, and were asked to judge which vowel sounded "clearer" by choosing one box from the two choices which were marked "Sound 1" and "Sound 2" respectively (see Appendix 29). The contrast pair was presented with one vowel preceding the other, with a 500 ms interval between the two vowels for comparison. Studies comparing pairs of vowel stimuli have used intervals between tokens of a length of 200 ms (Hazan & Markham, 2004), 500 ms (Kempster, Kistler, & Hillenbrand, 1991), and 1000ms (Kreiman, Gerratt, Precoda & Berke, 1992),

7.2.3 Stimuli

To include a range of voice samples representing different age groups and genders, a total of 40 speakers, with 5 females and 5 males in each of the four age groups (35+, 60+, 70+ 80+), were randomly selected from the list of participants included in the first experiment. From the recordings of each of these selected speakers, two sentences were randomly selected, including one sentence spoken using a normal jaw posture and the other an open jaw posture. From these two sentences, the full length of the steady portion of each of the four embedded vowels, /i, ɔ, u, a/, was segmented out and saved as a separate wave file, resulting in a total of 320 vowel segments (40 speakers X 2 jaw postures X 4 vowels). As shown in Table 20, this stimulus set consisted of vowel segments of variable lengths, ranging from 100.5 to 411.8 ms (Mean = 180.3 ms, SD = 62.3) for the "normal jaw" vowel segments and from 102.9 to 473.5 ms (Mean = 257.6 ms, SD = 83.2) for their "open jaw" counterparts. The average length for the vowel segments in the "variable length and intensity" ("variable") stimulus set was 218.8 ms (SD = 82.9).

Table 20. The range of the vowel length in the 'variable' data set used in the vowel clarity task for each of the four vowels / i, ɔ, u, a/; measured in milliseconds.

	Vowel Length (in ms)		
Vowel	Mean	Standard Deviation	Range
/i/			
Normal jaw	159.9	65.1	102.9 – 352.9
Open jaw	266.6	85.9	102.9 – 408.9
/ɔ/			
Normal jaw	158.3	44.5	100.5 – 264.7
Open jaw	214.0	64.0	102.9 – 387.2
/u/			
Normal jaw	194.0	77.4	102.9 – 411.8
Open jaw	286.6	84.2	127.4 – 452.9
/a/			
Normal jaw	209.1	40.89	130.0 – 307.7
Open jaw	263.9	82.0	132.3 – 473.5

From the “variable” stimulus set, two more sets with different stimulus specifications were generated, including one set of vowels with fixed length and one set of vowels with fixed length and normalised intensity. The “fixed length” stimulus set included vowel segments of a fixed length of 100 ms extracted from the mid-portion of the vowel segments in the “variable” stimulus set. The “fixed length and normalized” stimulus set included the “fixed length” vowel segments further normalised at 65 dB using the Adobe Audition 3 software. The three stimulus specifications, including “variable”, “fixed length”, and “fixed length and normalized”, were included to allow for consideration of the potential effect of signal duration or intensity on the perception of vowel intelligibility or clarity. The “fixed length” and “fixed length and normalized” stimulus sets were used in the vowel identification task and all of the three different stimulus sets (i.e., “variable”, “fixed length”, and “fixed length and normalized”) were used in the vowel clarity task.

To minimize the fatiguing effect, the testing time for each listener was controlled by having each listener tested on vowel samples taken from four speakers only. The stimulus sets containing vowel segments obtained from the recordings of the 40 selected speakers were organized into 10 stimulus groups, with two female and two male speakers randomly assigned to each of the 10 groups. Four listeners, two females and two males, were randomly assigned to be tested with one and only one of the 10 stimulus groups (termed A, B, C, D, E, F, G, H, J, K as shown in Appendix 32). In other words, each stimulus group, which contained vowels produced by two male and two female speakers, was tested on four and only four listeners. Stimulus groups B, G, and K included only native speakers of New Zealand English while all the other stimulus groups contained a mix of speakers with supposedly New Zealand, United States, United Kingdom, or South Africa accents (Appendix 32).

7.2.4 Instrumentation and Instrumental Setup

The system for presenting the stimuli included a desktop computer (Hewlett Packard Compaq NX6120), which was equipped with an internal sound card (Sound Max Digital Audio). A locally developed computer program written in C++ was installed in the computer for stimulus presentation and response recording. The computer screen was positioned at the participant's eye level. The distance between the participant and the internal computer speaker was kept relatively constant at approximately 60 to 70 cm.

7.2.5 Procedures

Each participant was seated in a double-walled quiet room. A five-trial practice run was presented and the volume of the computer was adjusted during the trial run to a comfortable level to the participant's satisfaction. After the comfortable level was identified for the participant, the volume remained the same for the remainder of the experimental session for that participant. The participant was asked to perform the participant's tasks. To limit auditory cues and prevent the presenter's voice from biasing the participant's responses, instructions for operating the computer software and descriptions of the participant's tasks were presented in written form on the computer screen (see Appendices 28 and 29). All participants had been informed, prior to entering the test room, that there would be minimum discussion immediately before the experiment or during the experimental session to minimise any influence the presenter's voice might have on the participant's perception of voice.

All participants started with the vowel identification task first. After being asked to perform the vowel identification task, the participant was presented, via the computer speaker, with a sequence of three blocks of vowels, with each block consisting of 32 tokens (4 speakers X 4 vowels X 2 jaw postures) presented in a pre-determined random order. The first block consisted of the "fixed length" stimulus set (32 tokens), the second the "fixed length and normalized" stimulus set (32 tokens), and the third the repeat of the first sequence (32 tokens), which was termed the "fixed length-R" stimulus set. After the vowel identification task was completed, the participant was asked to take a one to two minute break and then proceed with the vowel clarity task.

The procedure for the vowel clarity task consisted of sequential presentation of three randomized blocks of vowel pairs, with each block consisting of one and only one of the "variable", "fixed length", and "fixed length and normalized" stimulus sets. In other words, each vowel pair consisted of vowels spoken by the same speaker with (1) the same vowel and (2) the same stimulus specification (i.e., "variable", "fixed length", or "fixed length and normalised"). Each vowel pair was repeated twice, one with the "normal" posture in the first position and the other with the "open jaw" posture in the first position. The sequence of the vowel pairs was organized in a pre-determined random order. The participant was asked to take a one to two minute break around the middle of the vowel clarity task, which was at the point when 48 vowel pairs had been presented.

As the participant was allowed to replay the stimulus for each trial before providing an answer, the pause interval between trials was controlled by the participant. In average, the duration of the whole listening session was 15 minutes. The responses of the participants were automatically recorded onto separate text files for each sequence of testing.

7.2.6 Data Analysis

The responses recorded in the text files were processed for tabulation. Two sets of measurements were taken: one set from the vowel identification task, and the other set from the vowel clarity task. For the vowel identification task, the number of times each of the four vowels (/i, ɔ, u, a/) produced in each of the two jaw conditions (normal and open jaw) was correctly identified was counted in each of the three stimulus sets ("fixed length", "fixed length and normalized", and "fixed length-R") for each listener. For the vowel clarity task, the number of times each of the four vowels (/i, ɔ, u, a/) produced in each of the two jaw conditions (normal and open jaw) was judged to be "clearer" in a contrast pair was counted in each of the three stimulus sets ("variable", "fixed length", and "fixed length and normalised") for each listener.

7.2.7 Statistical Analysis

The same statistical analysis and plotting software used in the previous instrumental study was used in the follow-up perceptual study. The counts for the "correct identification" or "perceived as clearer" were transformed to a percentage score by dividing the target counts by the total occurrence of the vowel of interest. For the each of the three stimulus sets ("fixed length", "fixed length and normalized", "fixed length-R") tested in the vowel identification task, a series of two-way (2 jaw postures X 4 vowels) mixed model ANOVAs were performed on the "percent correct" scores to determine whether the identification scores were affected by jaw posture (normal and open jaw) as well as by vowel (/i, ɔ, u, a/) and the interaction between vowel and jaw posture.

For each of the three stimulus sets ("variable", "fixed length", and "fixed length and normalized") tested in the vowel clarity task, a series of chi-square tests were conducted to determine (1) whether open jaw posture was generally associated with a higher frequency of being perceived as "clearer", (2) whether the distribution of the counts of "being judged as clearer" between normal and open jaw postures differed for the three data sets, and (3) whether the effect of jaw opening on the perception of vowel clarity varied by vowel. In addition, individuals with a significant number of responses identifying the "open jaw" productions as being "clearer" than their "normal jaw" counterparts were counted. As each listener, in the vowel clarity task, was tested with 96 contrast pairs and asked to pick out the "clearer" of the two, the count of "open jaw posture" for being perceived as "clearer" was considered significantly higher than that of the "normal jaw posture" only upon reaching a value of 56. The derivation of this critical value was as follows:

Mean = Total number of contrast pairs/2 = 96/2 = 48

Standard deviation = Square root (total number of contrast pairs X 0.5 X 0.5)

= Square root (96 X 0.5 X 0.5) = 4.89

Standard score at significance level 0.05 (one-tailed test) = 1.65

Critical value = Mean + (standard score X standard deviation)

= 48 + (1.65 X 4.89) = 56

7.2.8 Reliability

Intra-listener total reliability was measured for the Vowel Identification Task for all listeners using the two stimulus sets (1) the fixed length stimulus and (2) a repeat of the fixed length stimulus set (fixed length repeated). Inter-listener total reliability was performed for all listeners on the Vowel Clarity Task using the three stimulus sets (1) fixed length (2) variable length and (3) fixed length normalised.

7.2.8.1 Vowel Identification Task

Intra-listener total reliability for the Vowel Identification Task was measured using two stimulus sets, the fixed-length and fixed-length repeated (a duplicate of the fixed-length stimulus set). Both stimulus sets were presented to the listeners during the same listening session. Each stimulus set contained 32 randomly presented vowels /i, ɔ, u, a/ from different speakers (4 speakers X 4 vowels X 2 jaw postures (normal and open)). A separate count was taken for each listener of the number of times each vowel was correctly identified in each of the two stimulus sets. Reliability was measured for each vowel by calculating the ratio of the number correctly identified in each of the two comparison stimulus sets. Total reliability was measured for all the listeners together and for each of the separate listener groups. Means, standard deviations, %minimum and %maximum for all 40 listeners together, and for each of the separate listening groups is presented in Table 21. Total reliability was found to be high.

Table 21. Intra-Listener total reliability in the vowel identification task from the Follow-up Perceptual Study for the two stimulus sets, fixed length and fixed length repeated. Each listening group consisted of two female and two male listeners.

	Number of Listeners	**Total Reliability %Mean (SD)**	**Minimum (%)**	**Maximum (%)**
All Listener Groups				
/a/	40	0.88 (0.14)	0.42	1.00
/ɔ/	40	0.86 (0.15)	0.40	1.00
/i/	40	0.80 (0.21)	0.25	1.00
/u/	40	0.85 (0.19)	0.14	1.00
Listener Groups				
/i/				
Group A	4	0.95 (0.12)	0.75	1.00
Group B	4	0.64 (0.33)	0.25	1.00
Group C	4	0.74 (0.24)	0.42	1.00
Group D	4	0.63 (0.13)	0.50	0.83
Group E	4	0.79 (0.23)	0.57	1.00
Group F	4	0.82 (0.23)	0.50	1.00
Group G	4	0.84 (0.23)	0.50	1.00
Group H	4	0.87 (0.25)	0.50	1.00
Group J	4	0.89 (0.07)	0.83	1.00
Group K	4	0.85 (0.19)	0.60	1.00
/ɔ/				
Group A	4	0.76 (0.11)	0.60	0.83
Group B	4	0.93 (0.07)	0.87	1.00
Group C	4	0.85 (0.01)	0.85	0.87
Group D	4	0.87 (0.08)	0.80	1.00
Group E	4	0.86 (0.17)	0.62	1.00
Group F	4	0.96 (0.07)	0.85	1.00
Group G	4	0.81 (0.28)	0.40	1.00
Group H	4	0.82 (0.21)	0.57	1.00
Group J	4	0.71 (0.21)	0.50	1.00
Group K	4	1.00 (0.00)	1.00	1.00
/u/				
Group A	4	0.93 (0.07)	0.87	1.00
Group B	4	0.87 (0.25)	0.50	1.00
Group C	4	0.76 (0.24)	0.37	1.00
Group D	4	0.96 (0.07)	0.85	1.00
Group E	4	0.87 (0.10)	0.75	1.00
Group F	4	0.69 (0.38)	0.14	1.00
Group G	4	0.83 (0.05)	0.75	0.87
Group H	4	0.69 (0.17)	0.50	0.87
Group J	4	1.00 (0.00)	1.00	1.00
Group K	4	0.96 (0.06)	0.87	1.00

	Number of Listeners	Total Reliability %Mean (SD)	Minimum (%)	Maximum (%)
/a/				
Group A	4	0.96 (0.06)	0.87	1.00
Group B	4	0.96 (0.06)	0.87	1.00
Group C	4	0.84 (0.20)	0.57	1.00
Group D	4	0.90 (0.06)	0.87	1.00
Group E	4	0.83 (0.15)	0.62	1.00
Group F	4	0.96 (0.06)	0.87	1.00
Group G	4	0.89 (0.13)	0.71	1.00
Group H	4	0.84 (0.11)	0.71	1.00
Group J	4	0.63 (0.15)	0.42	0.75
Group K	4	1.00 (0.00)	1.00	1.00

7.2.8.2 Vowel Clarity Task

Inter-listener total reliability was calculated on the Vowel Clarity Task from the three stimulus sets (1) fixed length, (2) variable length and (3) fixed length normalised. Each stimulus set contained 32 pairs of vowels (4 speakers X 4 vowels X 2 pairs arranged as normal/open or open/normal) for a total of 96 tokens (32 tokens X 3 stimulus set). The number of times an open jaw vowel was identified as clearer in a pair of normal/open or open/normal vowels was counted for each listener (x out of 96 tokens). A ratio of 'open jaw vowel as clearer' was calculated between each of the four listeners in their listening group (L1, L2, L3 and L4) and the other three listeners in their listening group (L1xL2, L1xL3, L1xL4, L2x L3, L2xL4, L3xL4), and a mean of the six ratios was then calculated. The mean, standard deviation, minimum and maximum values for all listening groups are presented in Table 22. Total reliability was found to be high.

Table 22. Inter-Listener total reliability in vowel clarity task from the Follow-up Perceptual Study for the three stimulus sets, fixed length, variable length and fixed length normalised presented for all listeners together, and for each of the separate listening groups.

	Number of Listeners	**Total Reliability % Mean (SD)**	**Minimum (%)**	**Maximum (%)**
All Listeners	40	0.866 (0.10)	0.57	1.00
Listening Groups				
Group A	4	0.83 (0.10)	0.70	0.98
Group B	4	0.81 (0.10)	0.69	0.98
Group C	4	0.87 (0.07)	0.76	0.98
Group D	4	0.93 (0.06)	0.87	1.00
Group E	4	0.82 (0.11)	0.61	0.94
Group F	4	0.94 (0.03)	0.89	1.00
Group G	4	0.97 (0.01)	0.95	1.00
Group H	4	0.83 (0.11)	0.70	0.96
Group J	4	0.75 (0.12)	0.57	0.92
Group H	4	0.88 (0.08)	0.80	1.00

7.3 Results

Statistical results were reported for the vowel identification and vowel clarity tasks separately in this section.

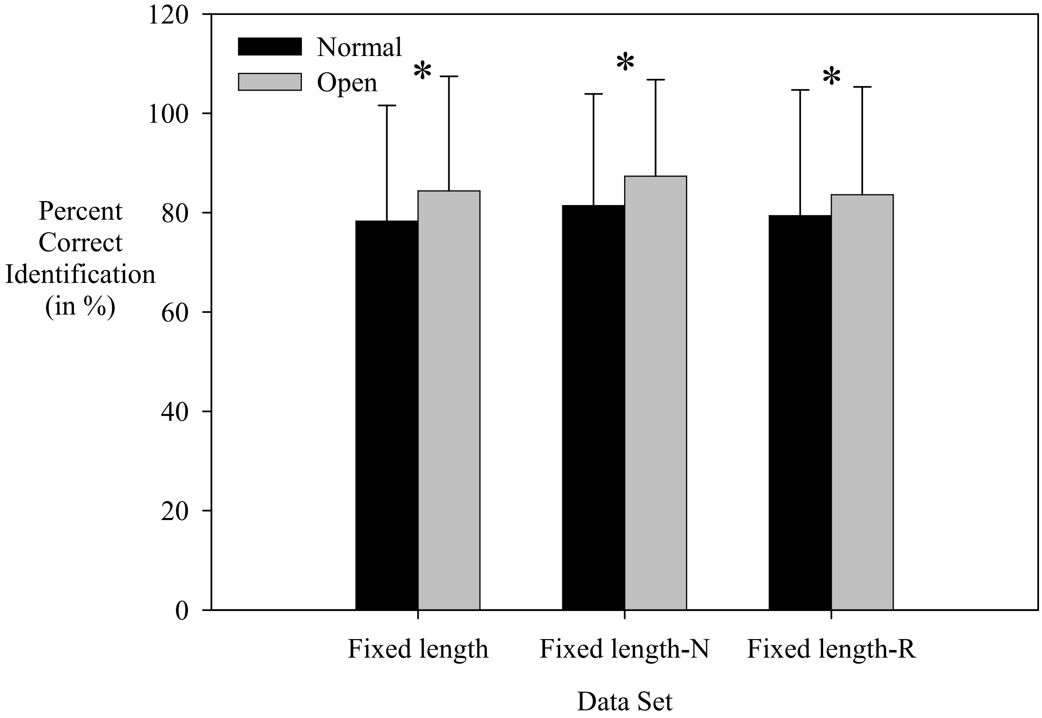
7.3.1 Vowel Identification

Results from a series of two-way (2 jaw postures X 4 vowels) mixed model ANOVAs conducted on the "percent of correct identification" scores for individual listeners tested with the three stimulus sets in the vowel identification task are shown in Table 23. As shown in Table 23, there was a significant jaw posture effect but no significant vowel by jaw posture interaction effect for all of three stimulus sets. The means and standard deviations for the "percent of correct identification" for the two main comparison groups (normal vs. open jaw) are shown in Figure 24. As shown in Figure 24, whether or not the stimuli were normalized, vowels produced with an "open jaw" posture were identified correctly more frequently than those produced in a normal posture.

Table 23. Results from two-way (2 jaw postures X 4 vowels) mixed model ANOVAs performed on the "percent of correct identification" scores for all listeners tested with the three stimulus sets ("fixed length", "fixed length and normalized", and "fixed length-repeated") in the vowel identification task.

	n	Vowel Effect	Posture Effect	Vowel x Posture Effect
All listeners included				
Fixed Length	320	$F(3, 117) = 2.082$, $p = 0.106$	$F(1, 39) = 8.475$, $\mathbf{p = 0.006}$*	$F(3, 117) = 1.299$, $p = 0.278$
Fixed Length and Normalised	320	$F(3, 117) = 2.048$, $p = 0.111$	$F(1, 39) = 14.994$, $\mathbf{p < 0.001}$**	$F(3, 117) = 0.744$, $p = 0.528$
Fixed Length-Repeated	320	$F(3, 117) = 9.990$, $\mathbf{p < 0.001}$**	$F(1, 39) = 5.435$, $\mathbf{p = 0.025}$*	$F(3, 117) = 0.074$, $p = 0.974$
Only listeners in the B, G, K Groups (i.e., stimuli produced by native speakers of New Zealand English only)				
Fixed Length	96	$F(3, 33) = 1.513$, $p = 0.229$	$F(1, 11) = 1.100$, $p = 0.339$	$F(3, 33) = 0.354$, $p = 0.787$
Fixed Length and Normalized	96	$F(3, 33) = 1.523$, $p = 0.227$	$\mathbf{F(1, 11) = 9.270, p = 0.011}$*	$F(3, 33) = 0.661$, $p = 0.582$
Fixed Length-Repeated	96	$\mathbf{F(3, 33) = 6.976, p < 0.001}$**	$F(1, 11) = 2.434$, $p = 0.147$	$F(3, 33) = 0.228$, $p = 0.876$

Figure 24. Vowel identification test results: Means and standard deviations of the "percent of correct identification" scores for vowels produced in two jaw postures (i.e., "normal" and "open" jaw postures) for each of the three stimulus sets, including "fixed length" and its repeated set (i.e., "fixed length" and "fixed length-R") and the "fixed length and normalized" ("fixed length-N") sets. Significantly different comparison pairs were marked with an asterisk ("*").

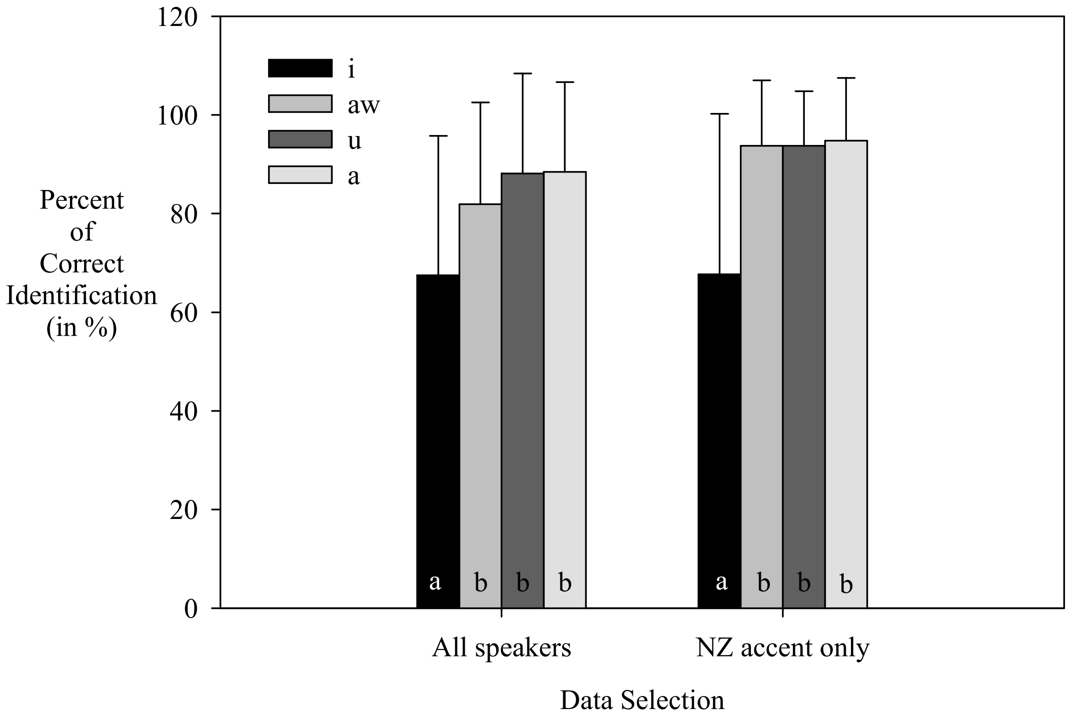


A significant vowel effect was also found in the "repeated" set for the "fixed length" stimuli ("fixed length-R"). Post hoc tests conducted on the scores obtained from the "fixed length-R" stimulus set revealed that the vowel /i/ had a correct identification rate significantly lower than all the other three vowels /ɔ, u, a/ (see Figure 25). An error analysis on the two high vowels /i/ and /u/ revealed that the majority of the incorrectly identified cases for /i/ were those where /i/ was mistaken as /e/ (76.1%) and that for /u/

were cases where /u/ was mistaken as /e/ (54.7%), suggesting that vowel confusion was related to the proximity between the vowels in the F1-F2 plot, which reflected the extent of tongue forwardness and tongue height.

Figure 25. Vowel identification test results: Means and standard deviations of the "percent of correct identification" scores for different vowels in the repeated set of the "fixed length" stimuli ("Fixed length-R") with the complete set of data ("All speakers") and with data obtained only from listeners in the B, K, and G stimulus groups, which contained vowels spoken only by native speakers of New Zealand English ("NZ accent only"). Significantly different comparison pairs were marked with different letters.

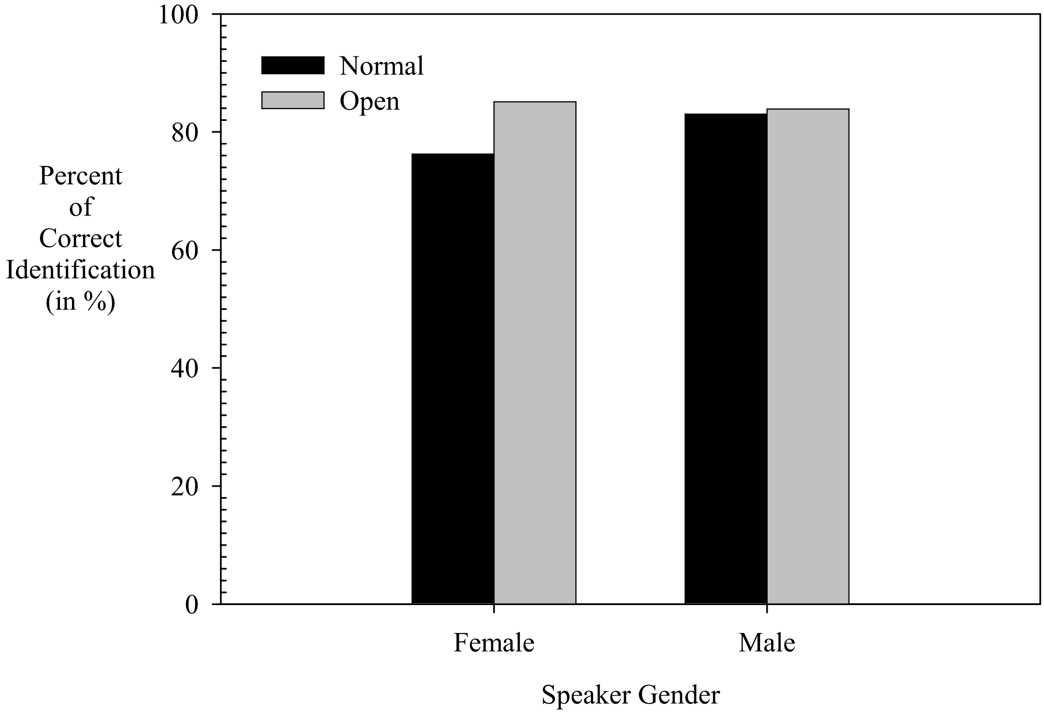
*Note: The vowel /ɔ/ is written as "aw" in the following figures.



For consideration about the speaker's accent on the listener's vowel identification performance, the same statistical analysis procedure as applied to the whole identification data set was performed on the data obtained from listeners assigned to the stimulus groups (Stimulus groups B, G, and K) which contained only vowels spoken by native speakers of New Zealand English (Appendix 32). As shown in Table 23, similar results were found, suggesting that the vowel and posture effects found in this study remained unaffected by the speaker's accent. As shown in Figure 25, post hoc testing for this "NZ accent only" data set also revealed that /i/ had the lowest and significantly different correct identification rate from all the other three vowels. It is noteworthy, however, that the jaw effect was found significant only for the "fixed and normalized" stimulus set with this smaller data set. This may be related to the lower within-group variation for vowel identification scores when the stimuli were controlled at the same intensity level. In other words, when the intensity levels of all vowels were kept equal, the effect of jaw posture on vowel identification would be less likely to be cancelled out or masked by the intensity effect.

With all the data obtained from the vowel identification task combined together, a comparison between normal and open jaw posture on the percent of correct identification was also made in vowels produced by male speakers and those by female speakers separately. As shown in Figure 26, the improvement induced by an open jaw posture was more evident in vowels produced by female speakers. This trend (i.e., open jaw effect on vowel identification being more evident when listening to female stimuli) appears to remain the same for all age groups, although a greater improvement (resulted from an open jaw posture) for female speakers than male speakers could be observed for the oldest age group (Appendix 33).

Figure 26. Vowel identification test results: The average percent of correct identification, with all the data obtained from the vowel identification task combined, for vowels produced by females and males in two jaw postures.



7.3.2 Vowel Clarity

The total count of "open jaw" productions being perceived as "clearer" and that of their "normal jaw" counterparts were shown for each of the stimulus sets separately in Figure 27. As shown in Figure 27, the "open jaw judged as clearer" group had the highest number of counts. Results from a series of chi-square tests conducted for the vowel clarity task are presented in Table 24. As shown Table 24, the distribution of the 1,280 counts (4 vowels X 2 contrast positions X 4 speakers X 40 listeners) of "being perceived as clearer" between the two jaw postures (normal and open) was the same for the "fixed length" and "fixed length normalized" stimulus sets but both were significantly different from the “variable” stimulus set. A visual inspection of Figure 27 revealed that the “open jaw judged as clearer” had the highest count in the “variable” data set amongst the three data sets. With responses obtained from all three stimulus sets combined (96 contrast pairs in total), 52.5% (21/40) of the listeners showed a significant count (i.e., greater than 56) for perceiving “open jaw” posture as “clearer”. Figure 28 shows the count of “open jaw posture being perceived as clearer” for individual listeners. A visual inspection of Figure 28 revealed that listeners who were assigned to listen to all vowels produced with New Zealand accent (Listeners 6, 10, 12, 14, 16, 20, 26, 27, 31, 34, 36, and 38, who were assigned to Group B, G, and K; as bolded in Appendix 32) generally did not appear to perform differently from those who were assigned to listen to vowels with different accents.

Table 24. Results of chi-square tests performed on the tallies of "open jaw productions judged as clearer" and "normal jaw judged as clearer" to determine the jaw effect in each of the three stimulus sets ("fixed length", "fixed length and normalized", and "variable") and to compare the distribution of these counts between the stimulus sets.

	Chi-square	df	p
Test of jaw effect:			
"Fixed length" alone	14.181	1	< **0.001****
"Fixed length and normalized" alone	7.461	1	**0.006****
"Variable" alone	42.207	1	< **0.001****
Test of stimulus effect:			
"Fixed length" vs. "Fixed length and Normalized"	0.993	2	0.319
"Variable" vs. "Fixed length"	7.316	2	**0.007****
"Variable" vs. "Fixed length and Normalised"	13.981	2	< **0.001****

**Significant at 0.01 level

Figure 27. Vowel clarity test results: Counts of being perceived as "clearer" for the two jaw postures (normal and open) in each of the three stimulus sets, including "variable", "fixed length" ("Fixed"), and "fixed length and normalized" ("Fixed-N"). The short dash line represents the critical value for reaching a statistically significant amount of count level.

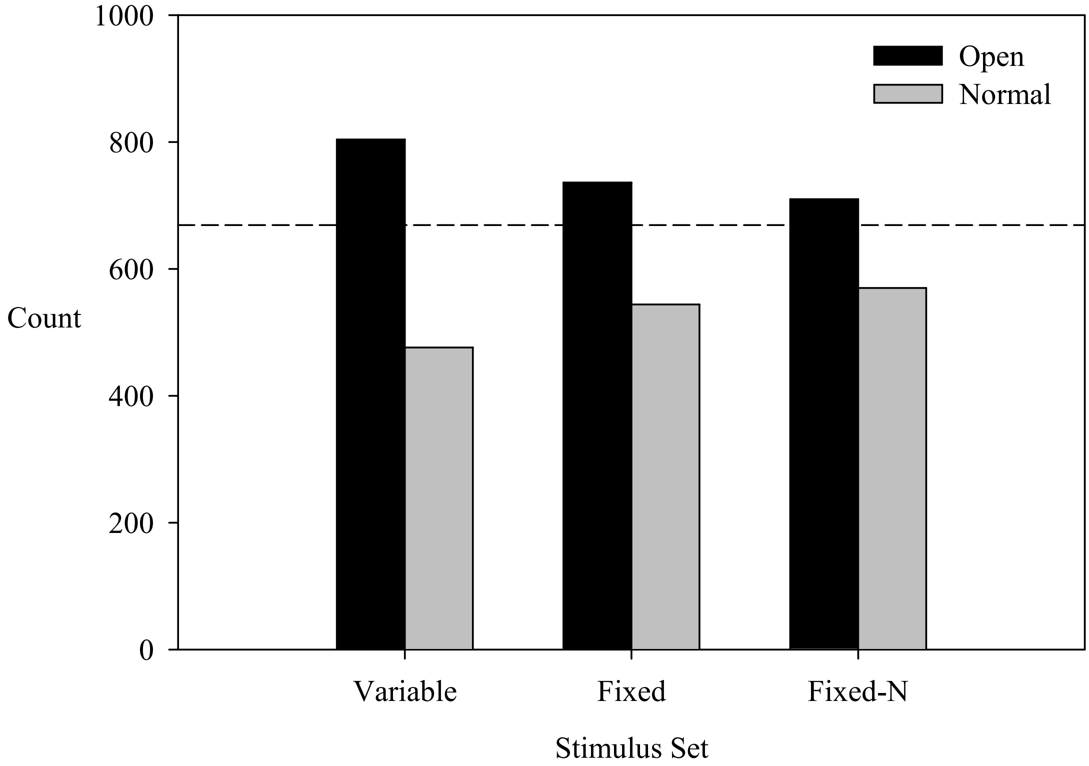
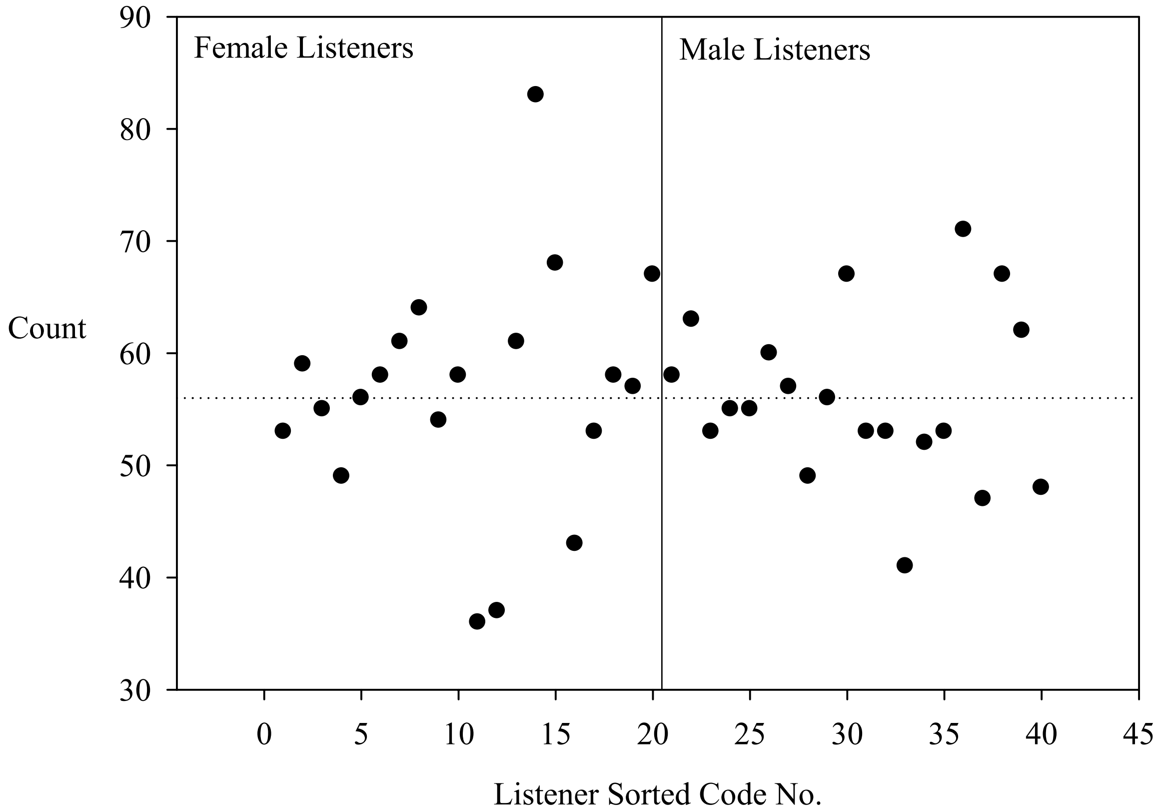
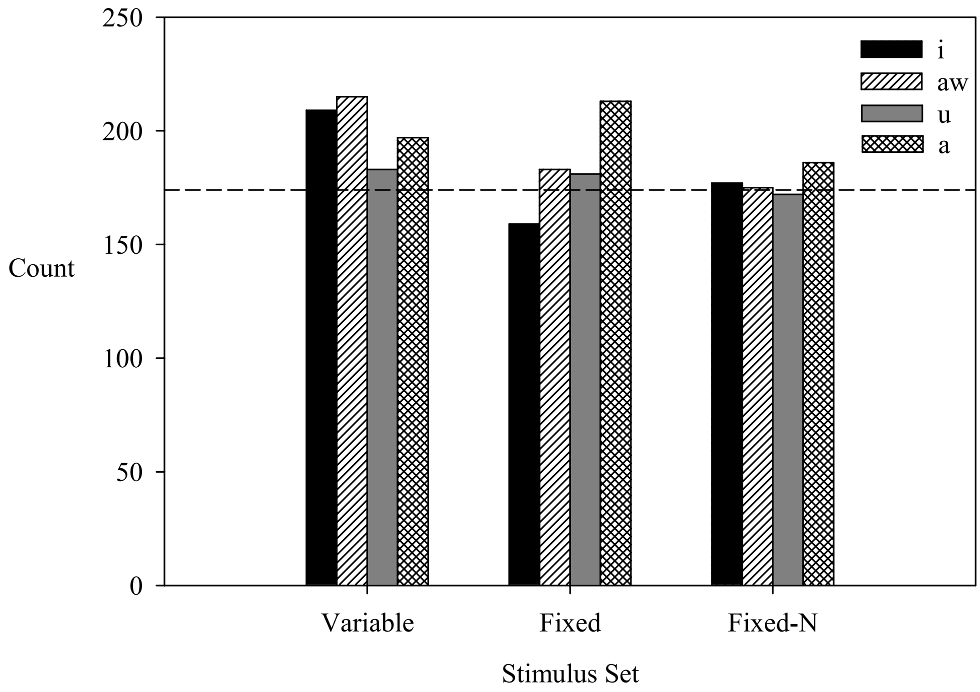


Figure 28. Vowel clarity test results: The total count of "open jaw posture being perceived as clearer", with responses to all three stimulus sets combined, for individual listeners. The dotted line represents the critical value for reaching a statistically significant amount of count level.



The distribution of the counts of “open jaw posture being perceived as clearer” was not found to differ between stimulus sets (chi-square = chi-square = 7.58, df = 6, p = 0.27) and no significant vowel effect was found in the “variable” (chi-square = 1.511, df = 3, p = 0.68), “fixed length” (chi-square = 3.968, df = 3, p = 0.265), or “fixed length and normalized” stimulus set (chi-square = 0.303, df = 3, p = 0.959). However, a visual inspection of Figure 29, which shows the counts of “open jaw Iosture being perceived as clearer” for each vowel (/i, ɔ, u, a/ in each stimulus set (“variable”, “fixed length”, and “fixed length and normalized”), revealed that the /i/ in the “fixed length” set and the /u/ in the “fixed length and normalized” stimulus sets did not reach a significant amount of count of “open jaw posture being perceived as clearer” (critical value = 174 using the same formula as described in 6.2.7, shown as a short dash line in Figure 29). This finding suggested that the contribution of an open jaw posture in improving vowel clarity was more evident in the “variable” stimulus set and the high vowels /i/ and /u/ might not benefit as much from an open jaw posture in terms of clarity if the potential effect of an open jaw posture on vowel duration or intensity was eliminated (as was the case in the “fixed length” and “fixed length and normalized” stimulus sets).

Figure 29. Vowel clarity test results: The total count of "open jaw posture being perceived as clearer" for each vowel in each of the three stimulus sets, including "variable", "fixed length" ("Fixed"), and "fixed length and normalized" ("Fixed-N") sets. The short dash line represents the critical value for reaching a statistically significant amount of count level.



7.4 Discussion

In a review of the current research on auditory-perceptual assessment, Oates (2009) reports that with adequate control of procedural variables, such as the design of the rating task, type of voice samples, and listener background and training, good measures of reliability and agreement can be achieved and that "perceptual evaluation could be reasonably robust" (p. 50). The methodology employed in the current study was designed to reduce factors that might negatively affect perceptual judgments and included controls on recorded intensity and duration of the vowel samples, withholding information about the speakers from the listeners so as not to bias or otherwise influence their auditory perceptions, and controlled environmental factors (double-walled room designed to reduce background noise, both limiting conversation and providing written instructions to avoid the influence of the examiner's voice on the perceptual task, and the self-setting by the listener of a comfortable listening intensity level).

The results from the follow-up perceptual study indicate that (1) vowels are more easily identified when they are phonated using an open jaw posture than when using a normal jaw posture and (2) vowels that are phonated in an open jaw posture are perceived more often by a listener as sounding "clearer" than vowels phonated using a normal jaw posture. These findings supported our hypotheses that the positive effect of an open jaw posture on voice as observed in the instrumental analysis in this study resulted in improved vowel intelligibility and vowel clarity.

7.4.1 Vowel Identification

The finding that the "percent of correct identification" was significantly higher for vowels produced in an open jaw posture as compared with those produced in a normal posture whether or not the vowel segments were normalized in intensity, suggested that the improvement induced by an open jaw posture for the speech quality was not solely due to the increased intensity. As the duration and intensity were kept constant in the "fixed length and normalized" data set, the finding in this data set that vowels produced in an open jaw also showed a greater "percent of correct identification" than those produced in a normal jaw suggests that an open jaw posture may result in positive change to the intrinsic properties of the vowel segment in addition to increasing duration and intensity. It has already been established in the instrumental investigation in this study that an open jaw posture could lead to improved phonatory stability and increased vowel space; the perceptual finding demonstrated that the positive acoustic effect induced by an open jaw posture would benefit vowel intelligibility. In particular, since it has been common consensus that formants play a key acoustic role in vowel identification (Peterson & Barney, 1952; Hillenbrand, Getty, Clark, & Wheeler, 1995), an open jaw posture may be one factor contributing to a greater movement of the formants from a centroid position, resulting in better differentiation among vowels. In this study, although the improved voice quality induced by an open jaw posture may also contribute to vowel intelligibility, it appears that the improved vowel intelligibility was largely, if not all, attributable to the increased vowel space due to an open jaw posture.

Although the jaw posture effect was found to apply to all vowels alike, the finding in the repeated test of the "fixed length" data set that the vowel /i/ tended to show a lower correct identification rate than the other three vowels, /ɔ, a, u/, may be related to a potential distortion effect induced by an open jaw posture to the high vowel /i/ vowel due to jaw lowering. However, as there was no significant vowel by jaw posture interaction effect and the other high vowel /u/ had similarly high rate of correct identification as other vowels, the potential vowel distortion effect induced by the jaw lowering in an open jaw posture might be minimal or vowel dependent. It is more likely that the vowel /i/ was naturally more easily confused with the other vowels due to its closer proximity to the vowel /e/, as compared with the other three vowels /ɔ, u, a/, in the F1-F2 plot, which reflected the extent of tongue forwardness and tongue height.

It is also noteworthy from the finding of the vowel identification task that the positive effect of an open jaw posture was more clearly shown in vowels produced by females than those produced by males. As found in the aerodynamic finding in the first experiment, females tended to produce a higher air pressure, as well as a higher mean flow rate, when using an open jaw posture than when using a normal jaw posture, the positive effect of an open jaw posture may be related to an improvement in the glottal function in transferring the aerodynamic energy to acoustic power due to the a better glottal closure with an open jaw posture as discussed in Section 6.3.2.3.

7.4.2 Voice Clarity

Vowels produced in an open jaw posture were found in this follow-up perceptual study to be perceived as “clearer” than those produced in a normal jaw posture most of the time. In comparing the findings from the “variable”, “fixed length”, and “fixed length and normalized” data sets, the positive open jaw effect was shown to be most prominent in the “variable” data set, suggesting that the open jaw posture might result in improvement in duration and intensity that would assist in improving the clarity of the sound quality. In the first experiment of this study, the sentence length and vowel length were both found to be longer in an open jaw posture than in a normal posture (see Appendix 22). One benefit of longer vowel phonation time is that it would contain more acoustic information which could then account for the increase in the perceptual judgement of clarity in vowels using an open jaw posture. This suggests that the lengthening of vowel duration, as preserved in the stimuli in the “variable” data set, may help improve vowel clarity. Specifically, as the stimuli in the “variable” data set were generally longer than the “fixed length” and “fixed length and normalized” data sets, the present finding the positive effect of an open jaw on the perception of vowel clarity was most evident in the “variable” data set suggests that when vowel length is longer, the vowel is judged to be clearer. In other words, an open jaw posture was useful in improving speech quality not only by changing the intrinsic properties of the vowel segment but also by increasing the vowel length.

A vowel effect on the clarity judgement was found for the “fixed length” data set but not in the “variable” or “fixed length and normalized” data sets. Analysis of the vowel effect found in the “fixed length” data set revealed that productions of /i/ with an open jaw posture were not as predominantly judged to be “clearer” than their “normal posture” counterparts as the other three vowels, /ɔ, a, u/, suggesting that the positive effect of an open jaw posture on vowel clarity was limited for the vowel /i/ if the comparison pairs were fixed in the same length but not normalized in intensity. This finding, along with the finding in the vowel identification task that the vowel /i/ tended to exhibit a lower rate of correct vowel identification, suggested that vowel clarity and vowel intelligibility are related. Another plausible explanation is that the clarity differentiation for the vowel /i/

may be more difficult because the vowel /i/, as shown in the first experiment, had a higher signal-to-noise ratio than the other vowels and thus the room for improvement in voice quality may be less than the other vowels. Therefore, only comparison pairs that were normalized in intensity (as those in the “fixed length and normalized” data set) and those consisting of more acoustic information due to a longer duration (as in the “variable” data set) would allow for better clarity differentiation for the vowel /i/.

Chapter 8. IMPLICATIONS, LIMITATIONS, AND CONCLUSIONS

This chapter provides a discussion of the clinical implications of this study, the limitations of the internal and external validity of the present findings, and the directions identified for future investigations, followed by a final conclusion.

8.1 Clinical Implications

The present finding provides empirical evidence showing that the aging voice of healthy adults is characterised by reduced loudness, increased phonatory instability, and changes to F0, VOT, vocal fold vibrating patterns (as measured by OQ and SQ), and vocal quality or clarity as measured by H1-H2 amplitude difference and frequencies of F1 and F2. Both acoustic and EGG measures were shown to be useful for detecting voice changes induced by aging.

Instrumental measurements from the sustained vowel /a/ in a one syllable task (normal, high, low pitch and /ma/ and /ha/- initiated) appeared more sensitive in identifying aging effects than measurements taken from the four embedded vowels (/i, ɔ, u, a/). In the case of females, aging effects from the sustained vowel /a/ one syllable tasks were found in F0, %jitter, %shimmer, SNR, F1, F2 and H1-H2, and for males in F0, %jitter, F1, F2 and H1-H2; whereas in the embedded vowel tasks aging effects were found in fewer acoustic measure, for females in F0, %jitter, SNR and F1, and for males in F0, %jitter and %shimmer. Except for the sustained vowel /a/, the other embedded vowels showed no age-induced effects. An increase in the variety of tasks, for example, changes in pitch and consonant initiated sustained vowels, appears to reveal more aging-related differences, than vowels embedded in sentences, suggesting that including more variety in the voicing task may be useful to enhance the sensitivity of the instrumental measures in detecting an aging effect.

One of the objectives of this study was to investigate the effect an open jaw posture has on acoustic measures in the aging population of healthy adults and whether such findings may then be used to assist in voice assessment and in management of the aging voice. Phonatory strategies that can demonstrate improved outcomes in an open jaw posture would be helpful in clinical programs managing voice disorders in the elderly. With the recognized growth of the aging population comes the increased need and patient expectation for age-appropriate voice therapy.

An open jaw posture may have already been included implicitly as a feature in certain clinical strategies, such as in the LSVT program for people with Parkinson's disease, because when patients are instructed to speak louder, they normally lower their jaw. The yawn-sigh approach, which is used to reduce laryngeal muscular tension, also incorporates an open jaw posture. The question is, can lowering the jaw be used as a clinical technique to help people who are experiencing problems with a voice changed as part of the normal aging process? In view of the evidence that there are aging-induced changes to the anatomical and physiological aspects of the speech and voice systems, the effect of jaw widening needs to be evaluated with the aging effect taken into consideration.

The changes to the elderly voice, as discussed above, often include changes in pitch, reduced SPL, greater phonatory instability and changes in voice quality. The results from this study have demonstrated that these phonatory characteristics improve in the elderly voice when the jaw is lowered and an open jaw posture may therefore be considered a useful approach to improve the aging voice. The evidence shown in this study in support of an open jaw posture are (see Appendix 35):

(1) Pitch: Fundamental frequency increased in open jaw for both genders and in all age groups. In a separate task, vowels sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated), where participants were asked to increase their pitch, a task effect on the acoustic measures %jitter, %shimmer, SNR and H1-H2 was observed. Examination of this task effect on measures of phonatory stability from the vowels sustained in a one-syllable task showed that when vowels were produced using a higher pitch, %jitter and %shimmer were lower and SNR was higher. In addition, the H1-H2 amplitude differences were lower when vowels were phonated using a higher pitch; lower H1-H2 amplitude differences have been associated with less breathy voice. The findings from this study suggest that the increase in F0 resulting from an open jaw may have the follow-on helpful effect of positive changes to voice quality. In addition, an increase in F0 might be particularly helpful for elderly women whose F0 tends to decrease with age. For males, the benefit of an increased pitch as a result of an open jaw posture may lie more in the change of voice quality than in pitch modification.

(2) SPL: Reduced loudness is frequently identified as one of the distinguishing features of the elderly voice. For both females and males, and in all age groups, SPL was found to increase in an open jaw posture.

(3) Phonatory stability: An open jaw posture has been shown useful in this study in improving phonatory stability, showing an effect of decreasing %jitter and %shimmer and increasing SNR. The improvement of %shimmer was more evident when observed in an isolated vowel sustained at normal pitch.

(4) Voice quality: The high incidence of vocal fold bowing as a result of normal physiological aging means that voice quality in the geriatric population would sound breathier. The H1-H2 amplitude difference was found to decrease in an open jaw posture for both females and males in all age groups. The significance of a decrease in H1-H2 amplitude difference is that this decrease is evidence of a less breathy voice and a voice produced with thicker vocal folds, which may contribute to a perceptually "thicker" sounding voice, thus counteracting the impression of an older weaker-sounding voice.

(5) Physiological changes: An open jaw posture was found to result in an increase in MFR for both genders and in OQ and air pressure for females.

(6) Speech intelligibility: In an open jaw posture the F1 and F2 frequencies for each of the embedded vowels (/i, ɔ, u, a,/), either increased or decreased in such a way that the net effect of vowel movement was a greater distance of the vowels from each other and where the direction of change resulted in an increase in vowel space area. This expansion of vowel space area in an open jaw was statistically significant for both females and males. Larger vowel space areas have been reported in the literature to be associated with improved speech intelligibility. In the follow-up perceptual study reported in Chapter 7, listeners were able to better differentiate among vowels spoken using an open jaw posture, and that a greater number of vowels produced in an open jaw posture were perceived as sounding clearer. These findings support a clinical role for the use of an open jaw posture approach in improving speech intelligibility and clarity. An open jaw is already a feature in some clinical strategies, e.g., the yawn-sigh approach, LSVT and Foreschel's chewing method.

8.2 Limitations of the Study and Future Directions

The technical limitations encountered in this study included difficulties in obtaining EGG recordings from some participants and in obtaining facial movement data from men with full beards. A procedural limitation faced was the small number of participants in a few of the male age groups; however, the numbers satisfactorily fulfilled the minimum sample size of 5 required for a factorial design study using analysis of variance (e.g., ANOVA) statistical tests.

It was not possible to record EGG signals from some participants. Colton and Conture (1990) found that recording EGG signals may be hindered by patients with thick or large necks, as well as in women who generally have smaller vocal folds and a wider thyroid cartilage angle than males (internal angles of around 120^o for females compared to around a 90^o angle in males). Because EGG recording systems use low current electrical signals to pass through layers of neck tissue to reach the vocal folds, large necks and/or a wide angled thyroid cartilages may inhibit the transduction of current through these tissues before reaching the area of the vocal folds. And it is the movement, or more precisely the period of vocal fold contact, that EGG systems are designed to record. Another technical difficulty encountered during voice recording is the interference to the sensing of the infrared light during tracking of the jaw movement. In the procedures for recording facial movement, small adhesive dots were placed on the tip of the nose, at each corner of the mouth and on the chin. Two males in the 60+ age group had full beards, and as a result we were not able to affix the dots to get reliable facial movement measurements.

The acoustic measures were extracted from sustained vowels and vowels embedded in words from a four word test sentence. Findings from both the instrumental and perceptual measurement showed that the use of an open jaw posture had positive effects across a variety of phonatory measures. Overall, it was found in this study that jaw posture had a particularly beneficial effect on the elderly voice, showing improvements in SPL, vocal quality, and intelligibility with an open jaw posture. Further research might investigate the effects of jaw opening on running speech in healthy adults over age 60.

Two other findings from this study suggest the need for further investigation. Firstly, we did not find statistically significant posture effects for measures of phonatory stability (%jitter, %shimmer and SNR), except in males for %jitter, and there was also considerable variability between the genders in the manner of change, i.e., either improvement or worsening in an open jaw posture. We saw improvement in the older males, but females showed no consistent pattern of change.

As the female participants showed a greater increase in jaw displacement in a open jaw posture and more evident changes of acoustic, EGG, and aerodynamic measures with an open jaw posture, further investigations are needed to determine whether there is an optimal range of jaw widening that would result in a positive change in speech and voice production. In particular, the gender difference in vocal behaviours in response to an open jaw posture needs to be examined closely. Elderly men and women with pathological voice also need to be included in future studies as the jaw posture effect shown in this study may be more evident in pathological voices where there is more room for improvement especially in perturbation measures. In addition, a closer look at the acoustic and physiological measures associated with the voices resulting in better speech intelligibility and clarity is also needed. As acoustic signals provide a physical link between production and perception, the simultaneous cross-system acoustic and physiological recording approach employed in this study is useful for relating the perceptual findings with the acoustic and physiological measures.

8.3 Conclusions

This study examined whether instrumental measures of phonatory variables would reveal differences along the aging continuum for females and males, and the effect an open jaw posture has on phonatory measures on the voice and vocal tact resonances of normally aging adults. The participants phonated the vowel /a/ sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and spoke a four word test sentence, in both a normal and an open jaw posture.

The findings in the current study show that instrumental measures are useful for identifying aging-induced changes in the voice and in vocal tract resonances. For acoustic measures, the female voice appeared to be more sensitive to the aging effect than the male voice. Significant age group effects for females were found on F0, %jitter, %shimmer, SNR, F2 and VOT, while for males, age group effects were found on F0 and VOT. Significant age group effects on the EGG measures SQ and OQ were found for both females and males in vowels sustained in a one-syllable task (i.e., normal, high, and low pitch and /m/ and /h/-initiated) and in the four embedded vowels. The large within-group variations in the measures reported in this study reflect the dissimilarities of the aging process in individuals of comparable chronological ages, and may explain the sometimes conflicting outcomes in studies of similarly aged individuals.

The findings in this study suggest that an open jaw approach may be useful in enhancing vocal stability and speech quality in the geriatric voice because it may lead increases in MFR, SPL, VOT, vowel space area (therefore better speech intelligibility). improved perturbation measures (%jitter for males) and decreases in the H1-H2 amplitude difference (thus achieving a less breathy voice). Results from the follow-up Perceptual Study showed that listeners were better able to identify vowels phonated in an open jaw posture, and that 'open jaw' vowels were more often judged to be perceptually 'clearer' than vowels spoken using a normal jaw posture. These data suggest that use of an open jaw posture may prove beneficial to the geriatric voice and consideration should be given to its possible inclusion in voice and speech therapy for this demographic group.

These results of the current study have implications for the clinical assessment and treatment of the elderly voice. Significant age group results were found for a number of acoustic measures and for different age groups. The finding that when the task is varied (i.e., by pitch and with a sustained vowel proceeded by a consonant), age group differences become more apparent, and suggests that inclusion of these features might play a beneficial role in clinical assessment of the elderly voice. An open jaw posture was found to have a positive effect on vowel space area, SPL, phonatory stability, H1-H2 amplitude differences, and VOT for both females and males. In addition, the changes in F1 and F2 frequencies as a result of an open jaw posture produced an expansion of the vowel space area, which from the literature suggests improved speech intelligibility. The findings from the follow-up perceptual study showed that vowels produced with an open jaw posture had higher rates of correct vowel identification (intelligibility) and greater judgements of vowel clarity. The above findings demonstrate the usefulness of an open jaw approach in the enhancement in speech and voice and support its use as a facilitative technique as part of a clinical strategy in the adult population.

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APPENDICES

Appendix 1. Participant Information Sheet

University of Canterbury
Department of Communication Disorders
Project Title: **Clinical Assessment Profile of the Geriatric Voice**

Investigators: Dr. Emily Lin and Helene Mautner
To: Potential research participants

You are invited to participate as a participant in a research project related to voice analysis.

Your involvement in this project will include speaking vowels and one-syllable words while we record your voice. When we record your voice, a microphone will be placed near your lips, two round-shaped plates will be placed on the two sides of the front of your neck, and four small pieces of stickers will be placed around your jaw and forehead. An airflow mask will be put over your face during airflow recording. The whole session should take no more than 40 minutes. You have the right to withdraw from the project at any time, including withdrawal of any information provided.

There is no risk in the performance of the tasks and application of the procedures.

You will be requested to provide a brief medical history, which will include questions about any neurological impairment, communication impairment, oral or facial surgery, respiratory illnesses, medication used and smoking and alcohol consumption.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: the identity of participants will not be made public. To ensure anonymity and confidentiality, the data will be secured in a locked cabinet in a secure office at the University of Canterbury.

The project is being carried out by a research Ph.D. student under the direction of Dr. Emily Lin, who can be contacted at 03-366-7001 ext: 7080. She will be pleased to discuss any concerns you may have about participation in the project. **Please ring Helene Mautner 366-7001 ext: 8465 or 021-0277-3863 to arrange for testing appointments.**

The project has been reviewed and approved by the University of Canterbury Human Ethics Committee.

Sincerely yours,

Helene Mautner, M.A.
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch
Telephone: 03-366-7001 ext: 8465
Email: hdm43@student.canterbury.ac.nz Mobile: 021-0277-3863

Appendix 2. Voice Interview Form

Name: ______________________________

Age: ______ Date of Birth ______ Female ❐ Male ❐

Occupation: ______________________________

Do you have any:

Respiratory Illnesses	Yes ❐	No ❐	________
Neurological impairments	Yes ❐	No ❐	________
Strokes	Yes ❐	No ❐	________
Head Injuries	Yes ❐	No ❐	________
Communication impairments	Yes ❐	No ❐	________
Oral or facial surgery	Yes ❐	No ❐	________
Hearing Problems	Yes ❐	No ❐	________
Endocrine/Hormone	Yes ❐	No ❐	________
Surgical History (major surgery)			
Head and neck	Yes ❐	No ❐	________
Abdominal	Yes ❐	No ❐	________
Respiratory/Chest	Yes ❐	No ❐	________
Other	Yes ❐	No ❐	________

Are you taking any medication?

Name of Medication	Frequency	Dosage

Speech History

Have you had: Voice training? Yes ❐ No ❐
Acting lessons Yes ❐ No ❐
Speech therapy Yes ❐ No ❐

Smoking History

_____ Never
_____ Quit. When ________________
_____ Smoked about _____ packs a day for ______ years
_____ Smoke now _____ packs per day. Have smoked for _____ years.

Alcohol

How much alcohol do you drink? [none] [rarely] [a few times per week] [daily]
If daily, or a few times per week, on the average, how much do you consume? [1, 2, 3, 4, 5, 6, 7, 8, or more] glasses per [day, week] of [beer, wine, liquor].

Caffeine

How many cups of [coffee, tea, cola other caffeine-containing drinks] per day? ___________

Interviewer:	Date:

Appendix 3. Agreement to participate

I have read the Participant Information Sheet and I agree to participate in the project "Clinical Assessment Profile of the Geriatric Voice" being held at the Communication Disorders Department of the University of Canterbury.

I understand that I may withdraw from the project at any time, including withdrawal of any information provided.

I understand that all information will be confidential and anonymity will be assured.

Name ____

Date ____

Helene Mautner, M.A.
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch
Telephone: 03-366-7001 ext: 8465
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Appendix 4. Aerodynamic recording protocols

Appendix 4.1 Airflow-EGG recording protocol

Sustained /a/ at normal pitch and loudness

Testing Sequence	Facial Posture	No. of Trials
1 – 5	Normal	5
6 – 10	Open	5
		Total = 10

Appendix 4.2 Airflow-air pressure-EGG recording protocol

Repeated sequence /pa-pa-pa-pa-pa/ at normal pitch and loudness

Testing Sequence	Facial Posture	No. Of Trials
1- 5	Normal	5
6 – 10	Open	5
		Total = 10

Appendix 5. Number of trials for productions of the vowel /a/ sustained in a one-syllable task (normal, high, and low pitch and /m/ and /h/-initiated)

Task No.	Task	Facial Posture	No. of Trials
1	/a/ Normal pitch	Normal	5
2	/a/ Low pitch	Normal	5
3	/a/ High pitch	Normal	5
4	/a/ Normal pitch	Open	5
5	/a/ Low pitch	Open	5
6	/a/ High pitch	Open	5
7	/ma/ normal pitch	Normal	5
8	/ma/ normal pitch	Open	5
9	/ha/ normal pitch	Normal	5
10	/ha/ normal pitch	Open	5
			Total = 50

Appendix 6. Number of trials for the production of the sentence "We saw two cars." at normal pitch and loudness level.

Jaw Posture	No. of Trials
Normal	10
Open	10
	Total = 20

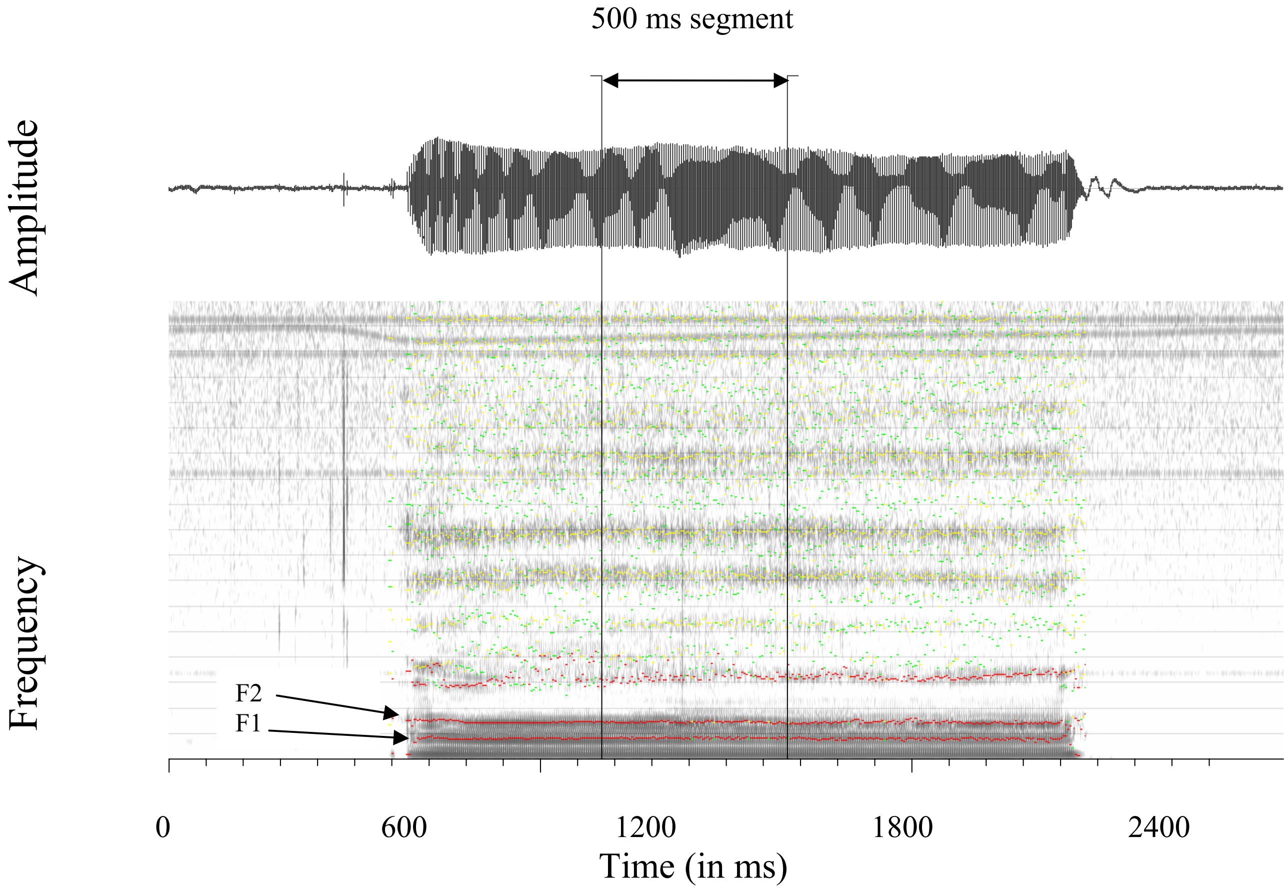
Appendix 7. Task sequence for acoustic-EGG-facial tracking recordings

Table Codes

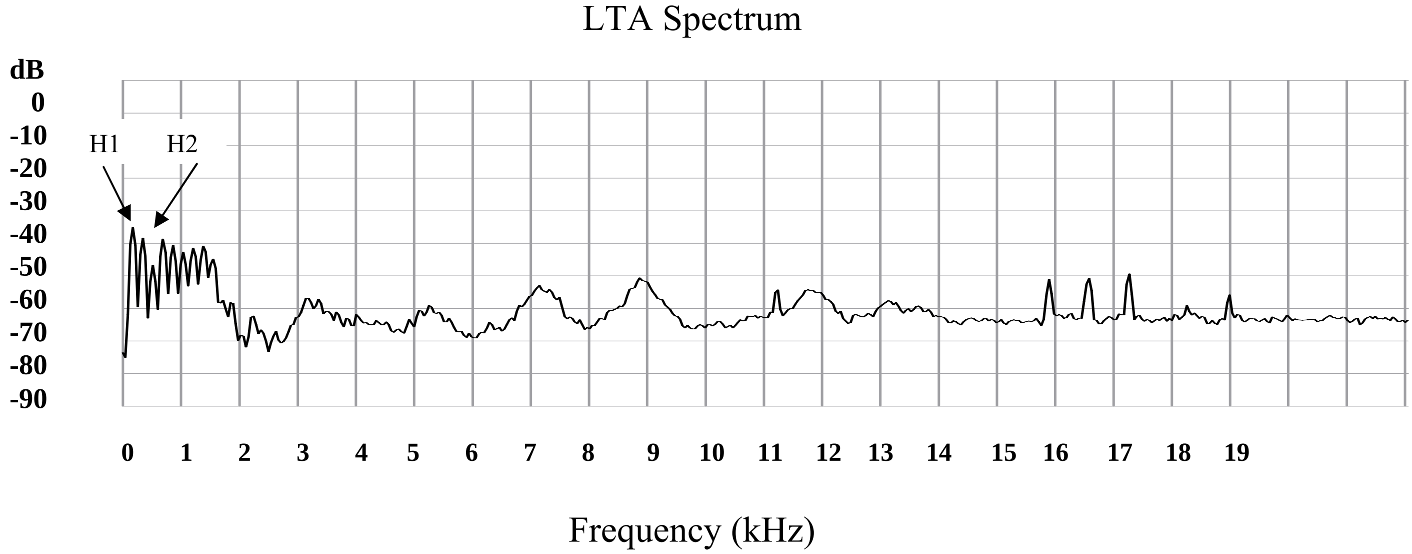
Posture			Tasks		
N	=	Normal facial posture	NP	=	Normal Pitch
O	=	Open Posture	LP	=	Low Pitch
			HP	=	High Pitch
			ma	=	/ma/ normal pitch
			ha	=	/ha/ normal pitch

Testing Sequence No.	Posture – Task	Testing Sequence No.	Posture – Task
1	N – NP	36	O – NP
2	N – LP	37	N – NP
3	N – HP	38	N – ma
4	O – NP	39	N – LP
5	O – LP	40	O – LP
6	O – HP	41	O sentence
7	N – ma	42	O sentence
8	O – ma	43	O sentence
9	N – ha	44	O sentence
10	O – ha	45	O sentence
11	O – NP	46	O – ma
12	N – LP	47	O – ha
13	N – HP	48	N – HP
14	O – ha	49	O – HP
15	N – NP	50	N - ha
16	N sentence	51	O – LP
17	N sentence	52	N – LP
18	N sentence	53	O – ha
19	N sentence	54	N – HP
20	N sentence	55	O – a
21	O – HP	56	N – ma
22	N – ma	57	O – HP
23	N – ha	58	N – ha
24	O – LP	59	O – ma
25	O – ma	60	N – NP
26	N – ma	61	N sentence
27	N - NP	62	N sentence
28	N – HP	63	N sentence
29	O – ma	64	N sentence
30	N – LP	65	N sentence
31	O – NP	66	O sentence
32	O – HP	67	O sentence
33	O – ha	68	O sentence
34	N – ha	69	O sentence
35	O – LP	70	O sentence

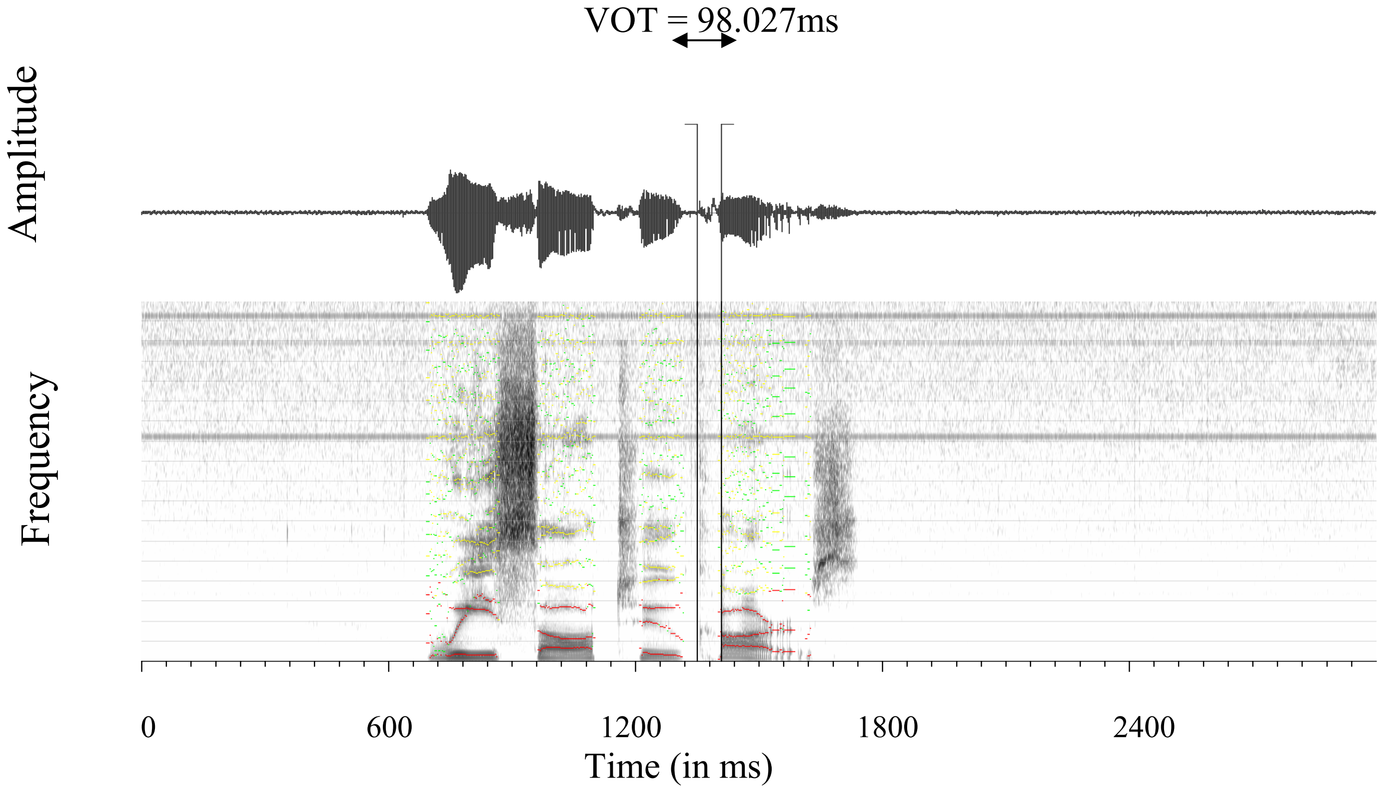
Appendix 8. Segment selection of the acoustic time waveforms with a display of the F1 and F2 tracings shown on the corresponding spectrogram



Appendix 9. First and second harmonics were selected using long-term average (LTA) spectrum without pre-emphasis. Spectrum: x-axis = frequency (in kHz), and y-axis = amplitude (in dB, starting from 0 at the top of graph down in increments of 10dB to -100dB).



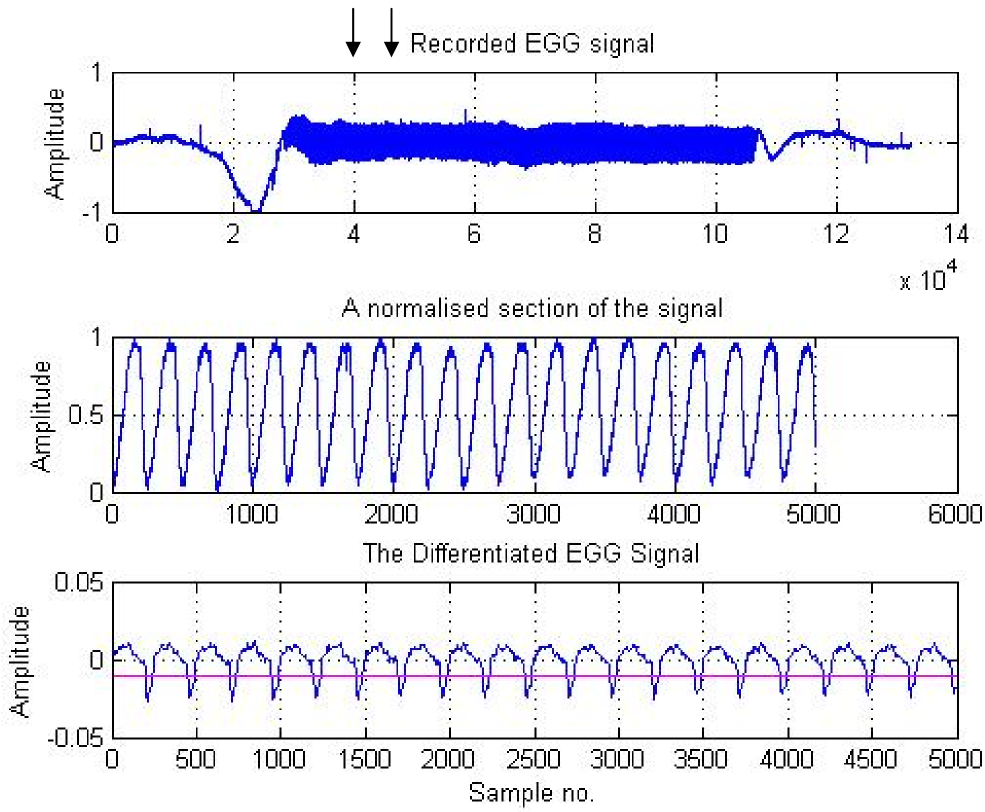
Appendix 10. VOT measurements were taken from for the word "cars" in the sentence "We saw two cars" from the release of the unvoiced plosive /k/ to the start of the vowel /a/. Top figure: time waveform (x-axis = time, y-axis = amplitude). Bottom figure: spectrogram (x-axis = time, y-axis = frequency).



W /i/ s /ɔ/ t /u/ **k /a/** r z
We saw two cars.

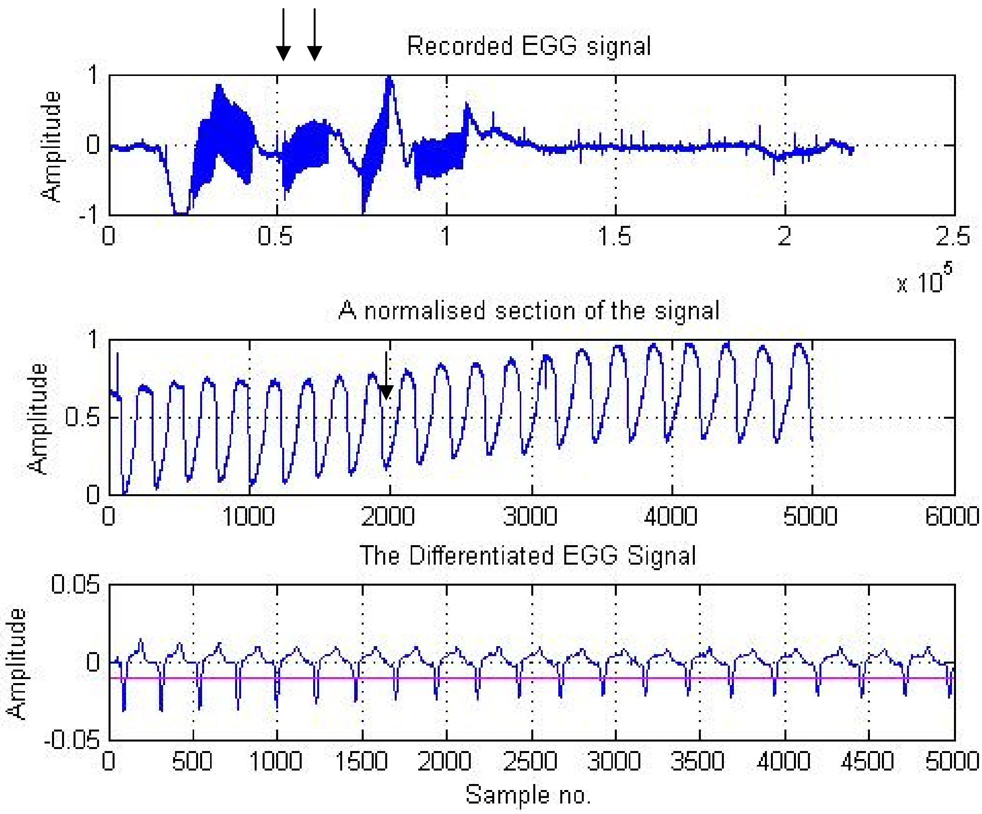
Appendix 11. EGG segment selections for sustained vowels

The top figure shows the recorded EGG signal for the sustained vowel /a/. The two arrows indicate the location of the steady 5,000 sample segment selected for analysis. Selection starts from approximately sample number 40,000 through sample number 45,000. The bottom figure shows the differentiated EGG signal of the selected segment used for analysis.



Appendix 12. EGG segment selection for embedded vowels

The top figure shows the recorded EGG signal for the sentence “We saw two cars.” The two arrows indicate the location of the steady 5,000 sample segment selected for the vowel /ɔ/ from the second word in the sentence /saw/. The selection starts from approximately sample number 51,000 through sample number 56,000. The bottom figure shows the differentiated EGG signal of the selected segment used for analysis.



Appendix 13. Age Information of EGG participants in different age groups

Appendix 13.1 Age Information of EGG participants in different age groups for the vowel /a/ sustained in a one syllable task (normal, high and low pitch, and /m/ and /h/-initiated).

Age Group	Females			Males		
	n	Min-Max	Mean (SD)	n	Min-Max	Mean (SD)
35+	10	38 – 56	48.2 (6.7)	5	42 – 57	49.0 (5.7)
60+	12	61 – 69	64.9 (3.1)	7	61 – 69	66.1 (3.0)
70+	6	70 – 77	73.0 (2.4)	7	70 – 78	74.2 (2.4)
80+	10	80 – 91	83.6 (3.3)	8	80 – 93	85.6 (4.4)

Appendix 13.2 Age Information of EGG participants in different age groups for the four vowels /i, ɔ, u, a/

Age Group	Females			Males		
	n	Min-Max	Mean (SD)	n	Min-Max	Mean (SD)
35+	9	38-56	47.3 (6.4)	3	42-47	45.3 (2.8)
60+	11	61-69	65.6 (2.9)	6	64-69	67.0 (2.0)
70+	5	70-77	72.8 (2.6)	4	70-78	74.2 (3.3)
80+	8	80-91	84.1 (3.3)	3	80-89	85.3 (4.7)

Appendix 14. Number and age range of participants as grouped by English accents

		New Zealand	British	U. S. A.	South African	Scottish	Irish
Females	n	38	7	7	2	1	1
	age	(40-91)	(44-87)	(38-68)			
Males	n	16	9	4	0	0	0
	age	(47-93)	(52-85)	(42-75)			

Appendix 15. Means and standard deviations of the acoustic measures organized by age group and jaw postures for the isolated vowel /a/ sustained at normal pitch by females.

	35+ (n = 14)	**60+ (n = 17)**	**70+ (n = 14)**	**80+ (n = 11)**
F0 (in Hz)				
Normal	194.9 (22.3)	179.7 (25.2)	189.0 (24.5)	169.5 (25.9)
Open Jaw	209.4 (21.8)	192.2 (32.4)	217.3 (30.0)	183.7 (25.4)
%jitter				
Normal	0.367 (0.11)	0.419 (0.20)	0.540 (0.43)	0.818 (0.48)
Open Jaw	0.405 (0.28)	0.378 (0.16)	0.411 (0.23)	0.890 (0.94)
%shimmer				
Normal	1.281 (0.25)	1.484 (0.46)	2.079 (1.61)	2.427 (0.95)
Open Jaw	1.446 (0.46)	1.570 (0.74)	1.670 (0.63)	2.605 (2.20)
SNR (in dB)				
Normal	25.55 (1.9)	25.23 (3.1)	23.78 (3.7)	22.69 (1.92)
Open Jaw	24.97 (2.6)	25.59 (3.5)	24.80 (2.6)	22.68 (2.32)
F1 (in Hz)				
Normal	859.2 (109.9)	846.9 (66.3)	841.9 (161.2)	830.5 (52.36)
Open Jaw	911.6 (87.1)	847.1 (92.1)	869.0 (137.2)	854.4 (70.60)
F2 (in Hz)				
Normal	1433.8 (133.6)	1347.5 (96.8)	1436.4 (109.0)	1426.1 (143.9)
Open Jaw	1418.1 (115.9)	1291.7 (75.9)	1411.1 (119.8)	1379.2 (127.4)
SPL (in dB)				
Normal	86.2 (4.8)	83.7 (5.4)	83.2 (5.4)	81.6 (6.2)
Open Jaw	89.9 (4.4)	85.9 (5.0)	86.3 (5.1)	84.1 (5.7)
H1-H2 (in dB)				
Normal	8.18 (2.73)	8.88 (2.83)	10.79 (3.84)	7.53(3.70)
Open Jaw	6.96 (2.50)	7.76 (3.28)	9.43 (3.53)	7.71 (3.92)

Appendix 16. Means and standard deviations of the acoustic measures organized by age group and jaw postures for the isolated vowel /a/ sustained at normal pitch by males.

	35+ (n = 5)	60+ (n = 7)	70+ (n = 8)	80+ (n = 9)
F0 (in Hz)				
Normal	104.2 (11.4)	111.8 (14.7)	127.3 (18.5)	133.9 (24.3)
Open Jaw	104.9 (12.8)	115.1 (14.7)	128.7 (16.9)	143.1 (23.8)
%jitter				
Normal	0.452 (0.13)	0.523 (0.141)	0.575 (0.50)	0.602 (0.22)
Open Jaw	0.430 (0.11)	0.435 (0.11)	0.454 (0.28)	0.471 (0.12)
%shimmer				
Normal	1.870 (0.351)	2.125 (0.216)	2.168 (0.855)	2.33 (0.884)
Open Jaw	2.052 (0.802)	1.928 (0.379)	1.838 (0.586)	2.104 (0.919)
SNR (in dB)				
Normal	24.27 (1.787)	22.63 (1.299)	23.35 (2.514)	22.62 (3.797)
Open Jaw	23.26 (2.573)	23.50 (2.307)	24.07 (2.294)	23.23 (2.875)
F1 (in Hz)				
Normal	657.8 (115.7)	725.5 (79.2)	715.2 (41.4)	710.5 (101.4)
Open Jaw	638.1 (58.3)	702.1 (71.5)	702.6 (41.0)	726.7 (91.5)
F2 (in Hz)				
Normal	1061.8 (123.8)	1199.3 (117.2)	1219.4 (97.8)	1260.0 (155.1)
Open Jaw	1075.0 (99.7)	1152.9 (111.3)	1191.9 (57.3)	1211.5 (126.4)
SPL (in dB)				
Normal	83.1 (2.3)	84.9 (5.0)	85.5 (4.4)	83.4 (4.6)
Open Jaw	85.8 (2.8)	89.8 (3.7)	87.7 (3.1)	85.8 (4.7)
H1H2 (in dB)				
Normal	13.07 (4.71)	8.72 (3.13)	8.32 (2.80)	11.17 (5.20)
Open Jaw	10.62 (5.06)	8.18(3.47)	7.04 (2.31)	10.73 (4.69)

Appendix 17. Means and standard deviations of the acoustic (F0, %jitter, %shimmer, SNR, F1, F2, H1-H2 amplitude difference, SPL, and VOT) and aerodynamic (MFR, air pressure) measures (with normal and open jaw combined) organised by gender and age group. All acoustic measures were obtained from the isolated vowel /a/ sustained at normal pitch except for VOT which was measured from the words "cars" and "two".

		Females (n = 56) Mean (SD)	**Males (n = 29)** Mean (SD)
F0			
	35+	202.155 (22.9)	104.211 (11.3)
	60+	185.966 (29.2)	111.776 (14.6)
	70+	203.159 (30.4)	127.334 (18.5)
	80+	176.577 (26.0)	133.866 (24.3)
%jitter			
	35+	0.3860 (0.20)	0.441 (0.11)
	60+	0.3980 (0.17)	0.479 (0.12)
	70+	0.4760 (0.34)	0.515 (0.39)
	80+	0.8540 (0.72)	0.537 (0.18)
%shimmer			
	35+	1.3630 (0.37)	1.961 (0.59)
	60+	1.5270 (0.60)	2.027 (0.31)
	70+	1.8750 (1.21)	2.003 (0.72)
	80+	2.5160 (1.65)	2.217 (0.88)
SNR			
	35+	25.2640 (2.25)	23.766 (2.15)
	60+	25.4110 (3.23)	23.064 (1.85)
	70+	24.2850 (3.16)	23.711 (2.35)
	80+	22.6820 (2.07)	22.924 (3.28)
F1			
	35+	885.371 (100.91)	647.940 (86.99)
	60+	846.976 (79.02)	713.800 (73.52)
	70+	855.471 (147.55)	708.913 (40.36)
	80+	842.436 (61.877)	718.589 (94.09)
F2			
	35+	1425.936 (123.02)	1103.640 (112.07)
	60+	1319.604 (90.20)	1176.057 (112.39)
	70+	1423.779 (113.13)	1205.637 (78.68)
	80+	1402.636 (134.79)	1236.233 (139.59)

	Females (n = 56) Mean (SD)	Males (n = 29) Mean (SD)
H1-H2		
35+	7.574 (2.64)	11.850 (4.79)
60+	8.322 (3.07)	8.453 (3.19)
70+	10.113 (3.68)	7.685 (2.57)
80+	7.626 (3.72)	10.953 (4.81)
VOT “cars”		
35+	84.447 (23.61)	102.996 (28.58)
60+	104.346 (31.72)	84.941 (24.03)
70+	102.156 (19.27)	76.771 (16.88)
80+	94.711 (28.69)	61.944 (12.89)
VOT “two”		
35+	86.661 (15.824)	103.346 (24.35)
60+	94.162 (18.873)	81.454 (21.80)
70+	89.047 (24.866)	74.825 (24.07)
80+	81.174 (12.866)	64.804 (11.97)
MFR		
35+	129.371 (49.003)	214.720 (129.887)
60+	125.141 (43.490)	201.814 (75.767)
70+	119.529 (67.789)	158.850 (51.438)
80+	147.691 (56.396)	158.436 (96.707)
Air Pressure		
35+	8.317 (2.330)	8.692 (1.700)
60+	8.674 (2.256)	8.281 (1.900)
70+	9.476 (2.742)	7.920 (1.742)
80+	9.130 (3.433)	9.574 (2.743)
SPL		
35+	88.054 (5.93)	84.540 (2.81)
60+	84.787 (5.42)	87.340 (4.95)
70+	84.762 (5.27)	68.348 (3.82)
80+	82.879 (4.93)	84.571 (4.66)

Appendix 18. Means and standard deviations of the experimental measures (with all age groups combined) organized by gender (female: n = 56, male: n = 29) and jaw posture for the isolated vowel /a/ sustained at normal pitch, unless where otherwise noted.

	Normal Jaw Posture Mean (SD)	**Open Jaw Posture** Mean (SD)
F0		
Females	183.8 (25.5)	201.1 (30.2)
Males	117.4 (20.2)	125.7 (22.5)
%jitter		
Females	0.515 (0.356)	0.494 (0.488)
Males	0.550 (0.291)	0.451 (0.168)
%shimmer		
Females	1.767 (1.023)	1.768 (1.166)
Males	2.157 (0.677)	1.979 (0.680)
SNR		
Females	24.448 (2.955)	24.665 (2.951)
Males	23.100 (2.626)	23.533 (2.427)
F1		
Females	845.4 (104.2)	870.1 (101.3)
Males	706.3 (84.6)	698.8 (72.8)
F2		
Females	1406.7 (122.8)	1370.3 (118.8)
Males	1212.4 (128.4)	1168.4 (108.7)
H1-H2		
Females	8.84 (3.3)	7.97 (3.3)
Males	10.12 (4.2)	9.08 (4.0)
MFR		
Females	122.3 (50.8)	134.0 (57.8)
Males	161.6 (71.1)	195.8 (103.6)
SPL		
Females	83.91 (5.4)	86.81 (5.2)
Males	84.31 (4.2)	87.35 (3.9)

	Normal Jaw Posture Mean (SD)	Open Jaw Posture Mean (SD)
Air Pressure (in cmH_2O)		
Females	8.101 (2.22)	9.417 (2.47)
Males	8.315 (1.71)	9.066 (2.55)
VOT "Cars" (in ms)		
Females	90.551 (23.1)	103.311 (29.7)
Males	74.498 (17.1)	82.828 (29.4)
VOT "Two" (in ms)		
Females	86.529 (16.8)	90.385 (16.8)
Males	75.598 (20.5)	80.867 (26.9)
Vowel Duration (in ms)		
"Cars"	682.3 (114.0)	818.9 (155.5)
"Two"	272.2 (95.9)	415.5 (168.3)

Appendix 19. Means and standard deviations of the acoustic measures organized by age group and jaw posture for the vowel /a/ embedded in the sentence "We saw two cars." produced by females.

	Vowel /a/ Embedded in the word "cars"			
	Females - Age Groups			
Number of Participants	**14**	**17**	**14**	**11**
F0 (in Hz)	**35+**	**60+**	**70+**	**80+**
Normal	170.6 (24.9)	161.7 (33.4)	176.1 (36.9)	159.2 (22.0)
Open Jaw	176.7 (24.9)	175.6 (40.5)	190.0 (45.6)	160.3 (22.8)
%jitter				
Normal	1.157 (0.82)	1.640 (1.09)	1.611 (1.31)	1.802 (1.07)
Open Jaw	1.005 (1.05)	1.078 (0.57)	1.300 (0.89)	1.386 (0.96)
%shimmer				
Normal	2.619 (1.23)	3.674 (1.84)	3.733 (3.39)	4.387 (2.68)
Open Jaw	2.511 (2.31)	2.828 (1.53)	3.315 (1.94)	3.561 (2.07)
SNR				
Normal	21.8 (2.97)	19.6 (3.36)	20.3 (4.54)	19.0 (2.99)
Open Jaw	21.6 (3.17)	21.4 (3.98)	20.4 (3.70)	19.2 (2.42)
F1				
Normal	876.5 (76.0)	859.2 (104.2)	868.4 (112.3)	824.2 (50.7)
Open Jaw	921.8 (106.1)	874.64 (98.2)	906.3 (137.7)	855.0 (85.0)
F2				
Normal	1532.1 (190.1)	1409.8 (188.2)	1576.7 (203.8)	1587.3 (176.1)
Open Jaw	1449.0 (190.3)	1322.7 (158.3)	1508.5 (190.8)	1497.0 (208.4)

Appendix 20. Means and standard deviations of the acoustic measures organized by age group and jaw posture for the vowel /a/ embedded in the sentence "We saw two cars." produced by males.

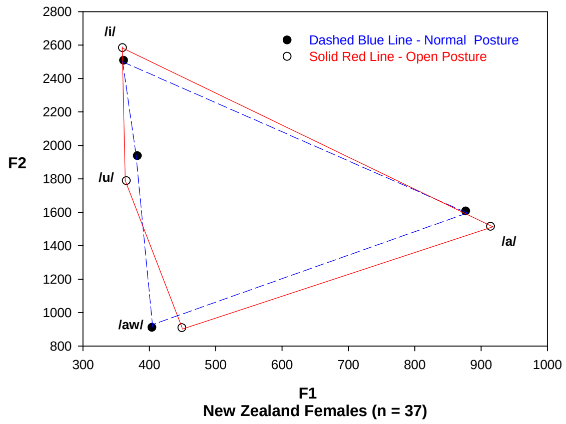
Vowel /a/ Embedded in the word "cars"

Males - Age Groups

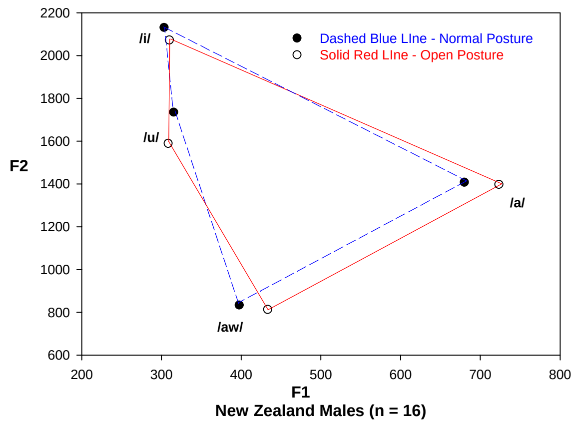
Number of Participants	**5**	**7**	**8**	**9**
	35+	**60+**	**70+**	**80+**
F0 (in Hz)				
Normal	91.0 (6.43)	101.9 (14.83)	120.3 (30.01)	117.6 (27.96)
Open Jaw	110.5 (41.64)	107.8 (14.67)	126.0 (36.14)	137.0 (33.62)
%jitter				
Normal	1.657 (1.51)	1.991 (1.37)	1.711 (0.68)	1.805 (1.38)
Open Jaw	2.267 (1.93)	1.143 (0.48)	1.562 (0.56)	1.479 (1.40)
%shimmer				
Normal	4.399 (3.72)	4.276 (1.52)	3.870 (1.49)	3.351 (1.56)
Open Jaw	5.623 (4.28)	3.151 (0.33)	3.637 (1.20)	3.421 (2.12)
SNR				
Normal	18.99 (4.08)	17.76 (3.26)	18.77 (2.90)	19.09 (4.85)
Open Jaw	17.81 (3.43)	19.37 (3.38)	18.13 (2.35)	19.87 (4.31)
F1				
Normal	586.04 (88.46)	709.37 (76.06)	667.28 (66.59)	631.69 (122.48)
Open Jaw	659.51 (130.87)	743.33 (70.53)	693.58 (49.28)	742.59 (106.69)
F2				
Normal	1124.86 (218.35)	1398.66 (129.16)	1292.24 (156.19)	1335.88 (189.35)
Open Jaw	1192.83 (347.55)	1376.16 (146.70)	1247.94 (146.21)	1439.36 (261.97)

Appendix 21. Vowel Space Area in Different English Accents

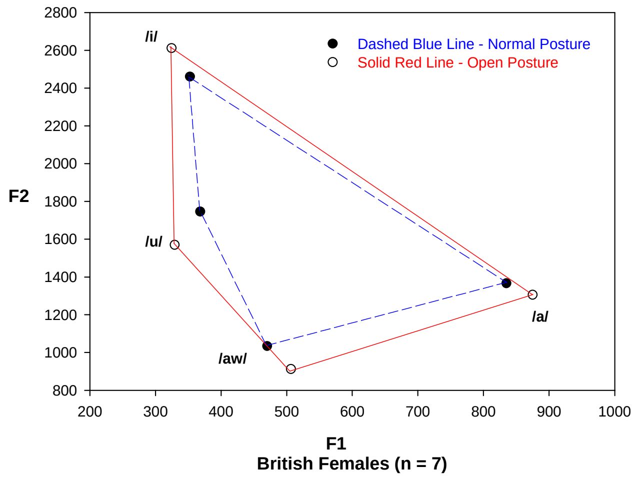
New Zealand Females



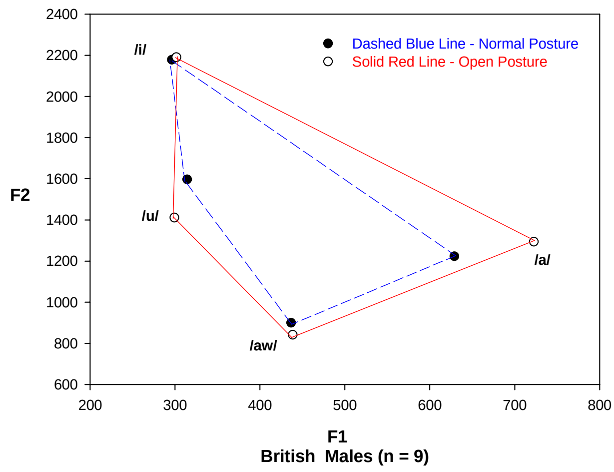
New Zealand Males



British Females

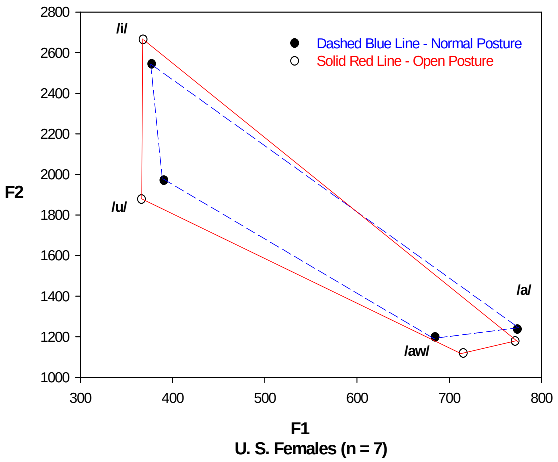


British Males

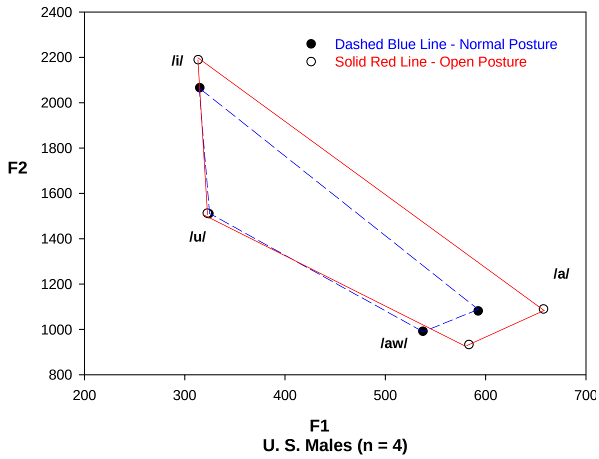


Appendix 21. (continued) Vowel Space Area – Different English Accents

U. S. Females



U. S. Males



Appendix 22. Means and standard deviations (in parentheses) of sentence and vowel durations (in ms) measured for the sentence "We saw two cars." produced in two jaw postures (normal and open).

	Female (n = 56)		**Male (n = 29)**	
	Normal jaw	**Open jaw**	**Normal jaw**	**Open jaw**
Sentence	1979.32 (574)	2880.30 (708)	1942.34 (414)	2558.13 (524)
/i/	167.78 (107)	317.17 (129)	172.86 (79)	290.34 (116)
/ɔ /	281.50 (134)	394.5 (105)	280.03 (77)	369.93 (84)
/u/	183.60 (93)	355.28 (137)	200.69 (83)	312.31 (92)
/a/	392.39 (87.8)	514.53 (114)	419.89 (59)	521.20 (87)

Appendix 23. Means and standard deviations (in parentheses) of mean duration (in ms) of the sentence “We saw two cars.” produced in a normal posture for different age groups.

Age Group	Female	Male
35+	1747.071 (440)	1972.400 (480)
60+	1883.375 (288)	2016.143 (459)
70+	2119.857 (530)	1942.750 (418)
80+	2214.250 (896)	1867.889 (403)

Appendix 24. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs for the vowel /a/ sustained in a one-syllable task excluding the isolated vowel at normal pitch

		n	Age effects	Posture Effects	Age x Posture Effects
				F0	
/ma/					
	Females	112	$F(3,52) = 2.534$, $p = 0.067$	$F(1,52) = 10.022$, $\mathbf{p = 0.003^*}$	$F(3,52) = 0.227$, $p = 0.877$
	Males	58	$F(3,25) = 4.183$, $\mathbf{p = 0.016^*}$	$F(1,25) = 18.362$, $\mathbf{p < 0.001^{**}}$	$F(3,25) = 3.292$, $\mathbf{p = 0.037^*}$
/ha/					
	Females	112	$F(3,52) = 2.060$, $p = 0.117$	$F(1,52) = 9.886$, $\mathbf{p = 0.003^*}$	$F(3,52) = 0.501$, $p = 0.683$
	Males	58	$F(3,25) = 3.670$, $\mathbf{p = 0.026^*}$	$F(1,25) = 11.076$, $\mathbf{p = 0.003^*}$	$F(3,25) = 2.021$, $p = 0.137$
Low Pitch					
	Females	112	$F(3,52) = 1.701$, $p = 0.178$	$F(1,52) = 53.761$, $\mathbf{p < 0.001^{**}}$	$F(3,52) = 1.169$, $p = 0.330$
	Males	58	$F(3,25) = 5.091$, $\mathbf{p = 0.007^*}$	$F(1,25) = 12.889$, $\mathbf{p = 0.001^*}$	$F(3,25) = 0.998$, $p = 0.410$
High Pitch					
	Females	112	$F(3,52) = 0.949$, $p = 0.424$	$F(1,52) = 58.712$, $\mathbf{p < 0.001^{**}}$	$F(3,52) = 2.700$, $p = 0.055$
	Males	58	$F(3,25) = 1.756$, $p = 0.181$	$F(1,25) = 14.916$, $\mathbf{p < 0.001^{**}}$	$F(3,25) = 0.437$, $p = 0.729$
				%jitter	
/ma/					
	Females	112	$F(3,52) = 2.151$, $p = 0.105$	$F(1,52) = 1.713$, $p = 0.196$	$F(3,52) = 1.903$, $p = 0.141$
	Males	58	$F(3,25) = 0.588$, $p = 0.628$	$F(1,25) = 1.774$, $p = 0.195$	$F(3,25) = 1.709$, $p = 0.191$
/ha/					
	Females	112	$F(3,52) = 3.011$, $\mathbf{p = 0.038^*}$	$F(1,52) = 0.264$, $p = 0.609$	$F(3,52) = 1.306$, $p = 0.282$
	Males	58	$F(3,25) = 0.570$, $p = 0.640$	$F(1,25) = 0.183$, $p = 0.673$	$F(3,25) = 1.978$, $p = 0.143$
Low Pitch					
	Females	112	$F(3,52) = 3.291$, $\mathbf{p = 0.028^*}$	$F(1,52) = 2.406$, $p = 0.127$	$F(3,52) = 0.793$, $p = 0.503$
	Males	58	$F(3,25) = 1.077$, $p = 0.377$	$F(1,25) = 1.131$, $p = 0.298$	$F(3,25) = 0.855$, $p = 0.477$
High Pitch					
	Females	112	$F(3,52) = 3.427$, $p = 0.024$	$F(1,52) = 2.244$, $p = 0.140$	$F(3,52) = 2.049$, $p = 0.118$
	Males	58	$F(3,25) = 1.036$, $p = 0.394$	$F(1,25) = 0.285$, $p = 0.600$	$F(3,25) = 0.844$, $p = 0.483$

	n	Age effects	Posture Effects	Age x Posture Effects
			%shimmer	
/ma/				
Females	112	F(3,52) = 4.047, p = **0.012***	F(1,52) = 0.0706, p = 0.792	F(3,52) = 2.823, **p = 0.048***
Males	58	F(3,25) = 0.756, p = 0.529	F(1,25) = 1.813, p = 0.190	F(3,25) = 1.517, p = 0.235
/ha/				
Females	112	F(3,52) = 3.363, **p = 0.025***	F(1,52) = 1.476, p = 0.215	F(3,52) = 0.992, p = 0.404
Males	58	F(3,25) = 0.315, p = 0.814	F(1,25) = 1.098, p = 0.305	F(3,25) = 2.635, p = 0.072
Low Pitch				
Females	112	F(3,52) = 1.892, p = 0.142	F(1,52) = 1.311, p = 0.258	F(3,52) = 0.980, p = 0.409
Males	58	F(3,25) = 0.356, p = 0.785	F(1,25) = 0.386, p = 0.540	F(3,25) = 0.899, p = 0.455
High Pitch				
Females	112	F(3,52) = 2.044, p = 0.119	F(1,52) = 7.154, **p = 0.010***	F(3,52) = 2.036, p = 0.120
Males	58	F(3,25) = 1.392, p = 0.268	F(1,25) = 0.170, p = 0.684	F(3,25) = 1.080, p = 0.375
			SNR	
/ma/				
Females	112	F(3,52) = 2.644, p = 0.059	F(1,52) = 0.400, p = 0.530	F(3,52) = 2.153, p = 0.105
Males	58	F(3,25) = 0.632,p = 0.601	F(1,25) = 1.103, p = 0.304	F(3,25) = 0.917, p = 0.447
/ha/				
Females	112	F(3,52) = 1.789, p = 0.161	F(1,52) = 2.648, p = 0.110	F(3,52) = 0.151, p = 0.928
Males	58	F(3,25) = 0.424, p = 0.738	F(1,25) = 0.0476, p = 0.829	F(3,25) = 1.929, p = 0.151
Low Pitch				
Females	112	F(3,52) = 5.795, **p = 0.002***	F(1,52) = 0.0611, p = 0.806	F(3,52) = 0.367, p = 0.777
Males	58	F(3,25) = 0.635, p = 0.600	F(1,25) = 0.0654, p = 0.800	F(3,25) = 1.538, p = 0.229
High Pitch				
Females	112	F(3,52) = 1.555, p = 0.211	F(1,52) = 0.382, p = 0.539	F(3,52) = 0.674, p = 0.572
Males	58	F(3,25) = 1.394, p = 0.268	F(1,25) = 0.918, p = 0.347	F(3,25) = 0.745, p = 0.536
			F1	
/ma/				
Females	112	F(3,52) = 2.326, p = 0.085	F(1,52) = 0.241, p = 0.625	F(3,52) = 0.836, p = 0.480
Males	58	F(3,25) = 1.406, p = 0.264	F(1,25) = 2.202, p = 0.150	F(3,25) = 0.0987, p = 0.960
/ha/				
Females	112	F(3,52) = 0.946, p = 0.425	F(1,52) = 0.230, p = 0.633	F(3,52) = 0.915, p = 0.440
Males	58	F(3,25) = 0.996, p = 0.411	F(1,25) = 0.318, p = 0.578	F(3,25) = 0.975, p = 0.420
Low Pitch				
Females	112	F(3,52) = 1.157, p = 0.335	F(1,52) = 1.114, p = 0.296	F(3,52) = 1.602, p = 0.200
Males	58	F(3,25) = 2.758, p = 0.063	F(1,25) = 0.104, p = 0.750	F(3,25) = 1.253, p = 0.312
High Pitch				
Females	112	F(3,52) = 1.358, p = 0.266	F(1,52) = 3.581, p = 0.064	F(3,52) = 0.185, p = 0.906
Males	58	F(3,25) = 1.107, p = 0.365	F(1,25) = 0.435, p = 0.515	F(3,25) = 1.248, p = 0.313

	n	Age effects	Posture Effects	Age x Posture Effects
		F2		
/ma/				
Females	112	F(3,52) = 2.239, p = 0.095	F(1,52) = 16.224, **p < 0.001****	F(3,52) = 0.0779, p = 0.972
Males	58	F(3,25) = 1.416, p = 0.261	F(1,25) = 0.648, p = 0.428	F(3,25) = 0.221, p = 0.881
/ha/				
Females	112	F(3,52) = 2.542, p = 0.066	F(1,52) = 31.002, **p <0.001****	F(3,52) = 0.460, p = 0.712
Males	58	F(3,25) = 0.930, p = 0.441	F(1,25) = 1.365, p = 0.254	F(3,25) = 0.641, p = 0.595
Low Pitch				
Females	112	F(3,52) = 1.235, p = 0.306	F(1,52) = 10.273, **p = 0.002***	F(3,52) = 0.222, p = 0.880
Males	58	F(3,25) = 1.651, p = 0.203	F(1,25) = 5.936, **p = 0.022***	F(3,25) = 1.074, p = 0.378
High Pitch				
Females	112	F(3,52) = 3.138, **p = 0.033***	F(1,52) = 2.081, p = 0.155	F(3,52) = 2.283, p = 0.090
Males	58	F(3,25) = 1.445, p = 0.253	F(1,25) = 0.0033, p = 0.937	F(3,25) = 0.501, p = 0.685
		H1-H2		
/ma/				
Females	112	F(3,52) = 2.235, p = 0.095	F(1,52) = 9.407, **p = 0.003***	F(3,52) = 0.490, p = 0.691
Males	58	F(3,25) = 2.744, p = 0.064	F(1,25) = 4.585, **p = 0.042***	F(3,25) = 0.693, p = 0.565
/ha/				
Females	112	F(3,52) = 1.070, p = 0.370	F(1,52) = 22.134, **p <0.001****	F(3,52) = 1.457, p = 0.237
Males	58	F(3,25) = 1.366, p = 0.276	F(1,25) = 3.899, p = 0.059	F(3,25) = 0.424, p = 0.738
Low Pitch				
Females	112	F(3,52) = 1.648, p = 0.190	F(1,52) = 9.669, **p = 0.003***	F(3,52) = 2.584, **p = 0.063***
Males	58	F(3,25) = 0.611, p = 0.614	F(1,25) = 3.653, p = 0.068	F(3,25) = 1.707, p = 0.191
High Pitch				
Females	112	F(3,52) = 0.250, p = 0.861	F(1,52) = 24.099, **p <0.001****	F(3,52) = 1.219, p = 0.312
Males	58	F(3,25) = 1.434, p = 0.257	F(1,25) = 11.963, **p = 0.002***	F(3,25) = 0.935, p = 0.439

Appendix 25. Participant Information Sheet – Perceptual Study

University of Canterbury
Department of Communication Disorders
Project Title: Perception of Vowel Clarity

Investigators: Dr. Emily Lin and Helene Mautner

To: Potential research participants

You are invited to participate as a listener/judge in a research project related to voice analysis. To participate in this study, English must be your first language. It will take less than an hour and you will be compensated for your time with a $10 petrol voucher.

Your involvement in this project will include listening to pairs of sounds and making judgments as to which one sounds 'clearer' and listening to a sound and judge which vowel you think you have heard. You will be seated in a quiet room while the voice samples are played to you through a computer.

There is no risk in the performance of the tasks and procedures.

You will be requested to provide some personal information, including your name, age, gender, place of birth, and language background. You will also be asked to take a short hearing screening test which will be administered by an experienced audiologist. You will be advised of the results of the hearing screening test and if a hearing loss is identified you will be informed of further hearing testing options.

All data will be saved anonymously and stored in a locked cabinet in the Communication Disorders Department. Data will be destroyed after twelve years unless another application has been made and approved to keep the data for a longer period of time.

The project is being carried out by a research Ph.D. student under the direction of Dr. Emily Lin, who can be contacted at 03-366-7001 ext: 7080. She will be pleased to discuss any concerns you may have about participation in the project. **Please ring Helene Mautner 366-7001 ext: 8465 to arrange for appointments.**

The project has been reviewed and approved by the University of Canterbury Human Ethics Committee.

Sincerely yours,

Helene Mautner, M.A.
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch
Telephone: 03-366-7001 ext: 8465 Email: hdm43@student.canterbury.ac.nz

Appendix 26. Agreement to Participate – Perceptual Study

I have read the Listener Information Sheet and I agree to serve as a judge in the project "Perception of Vowel Clarity Project" being held at the Communication Disorders Department of the University of Canterbury.

I understand that I may withdraw from the project at any time, including withdrawal of any information provided.

I understand that all information will be confidential and anonymity will be assured.

Name____

Date ____

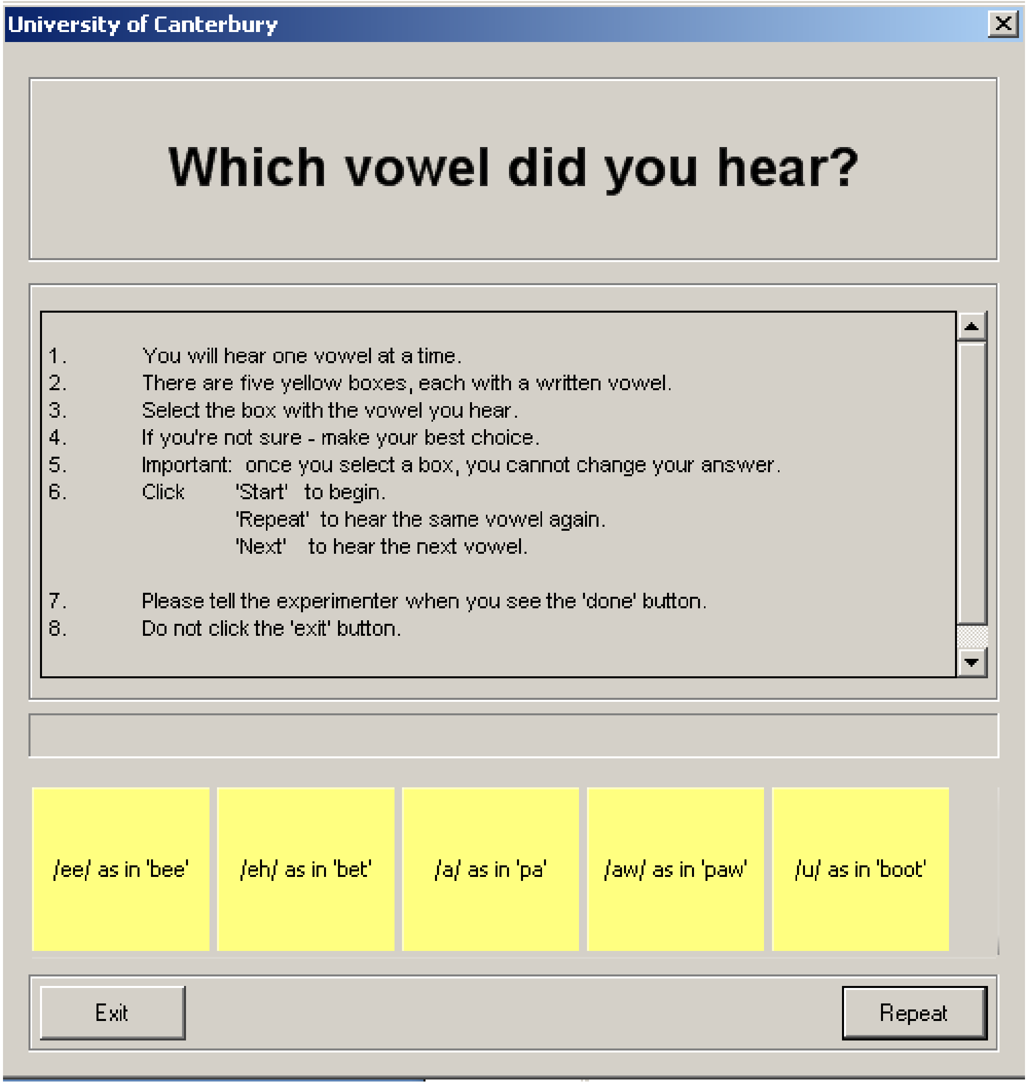
Helene Mautner, M.A.
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch
Telephone: 03-366-7001 ext: 8465
Email: hdm43@student.canterbury.ac.nz

Hearing Screening Test Passed Yes ❒ No ❒

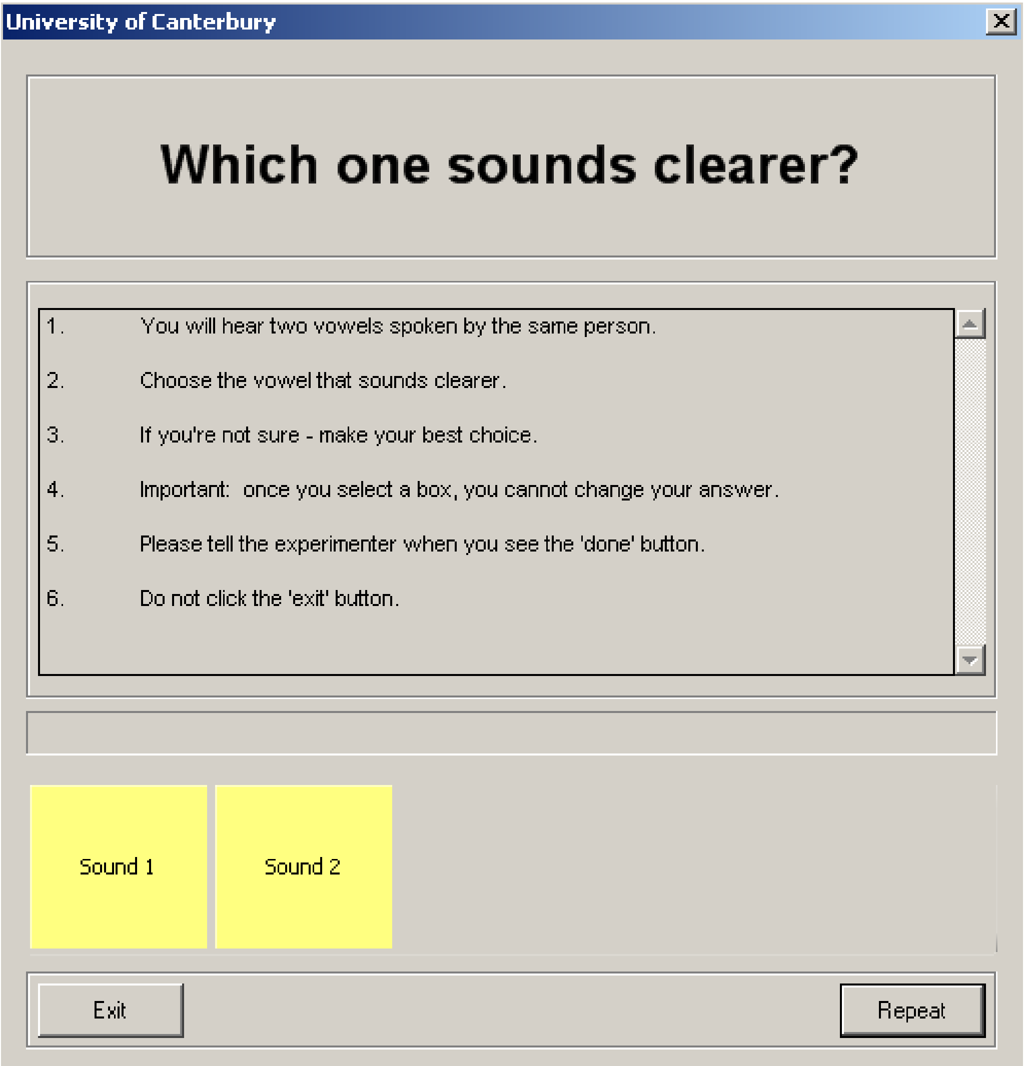
Appendix 27. Participant Background Sheet – Perceptual Study

Name:		
Age:	Female ❒	Male ❒
Country of birth:		
Is English your first language?	Yes ❒	No ❒
What language was spoken at home?	English ❒	Other ❒
If your country of birth is <u>not</u> NZ, at what age did you move to NZ?		
If you were born in NZ, then later moved away:	At what age did you leave? __________ How long were you away? __________	

Appendix 28. Interface for the Vowel Identification Task



Appendix 29. Interface for the Vowel Clarity Task



Appendix 30. Vowel Pairs for Each Speaker*.

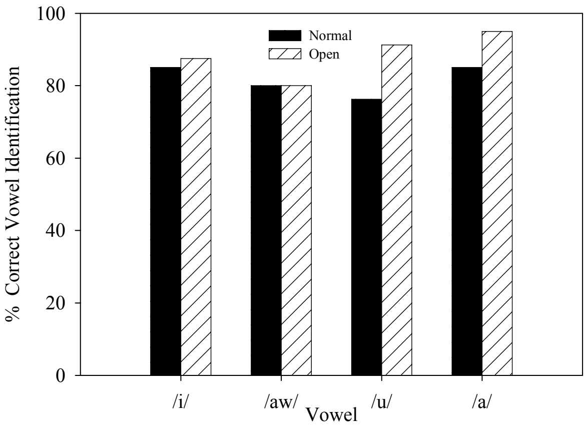
	Variable Length Vowel order	Variable Length Vowel Order	Fixed Length Vowel Order	Fixed Length Vowel Order	Fixed Length Normalised Vowel Order	Fixed Length Normalised Vowel Order
/i/	N/O	O/N	N/O	O/N	N/O	O/N
/ɔ/	N/O	O/N	N/O	O/N	N/O	O/N
/u/	N/O	O/N	N/O	O/N	N/O	O/N
/a/	N/O	O/N	N/O	O/N	N/O	O/N

* Vowel Order
N/O = Normal first then open jaw posture.
O/N = Open jaw posture first then normal.

Appendix 31. Listening Study: Figures of means and standard deviations for female and male listeners of percent of correctly identified vowels' and 'percent vowels judged clearer' for the different vowel segment length format types for the Vowel Identification Task, fixed length (1), fixed length normalised and fixed length (2), and for the Vowel Clarity Task, fixed length, variable length and fixed length normalised.

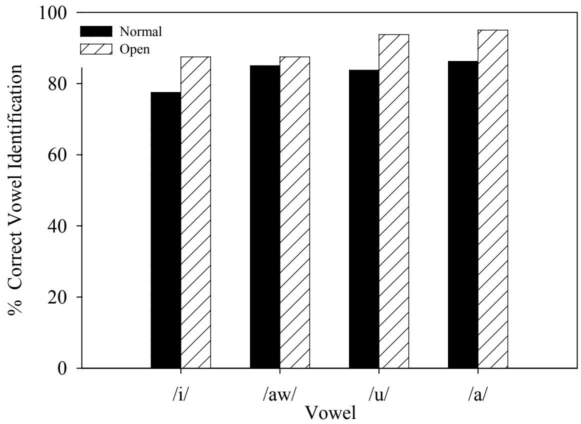
*Note: The vowel /ɔ/ is written as “aw” in the following figures.

Appendix 31.1 - Female Listeners Vowel Identification Fixed Length (1)



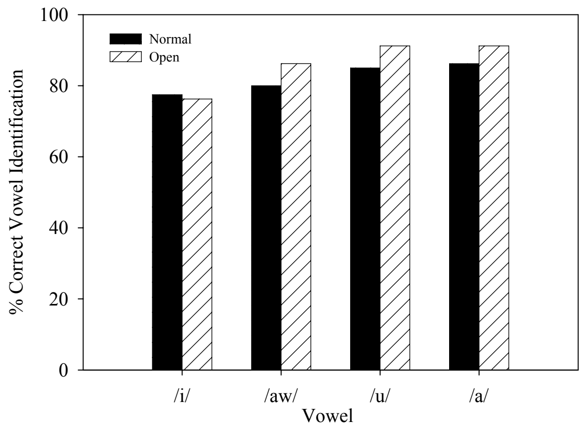
Fixed Length (1)
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.2 - Female Listeners Vowel Identification Fixed Length Normalised (65dB)



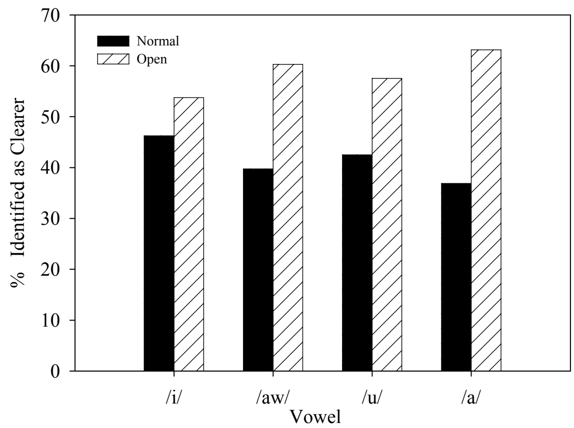
Fixed Length and Normalised (65dB)
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.3 - Female Listeners Vowel Identification Fixed Length (2)



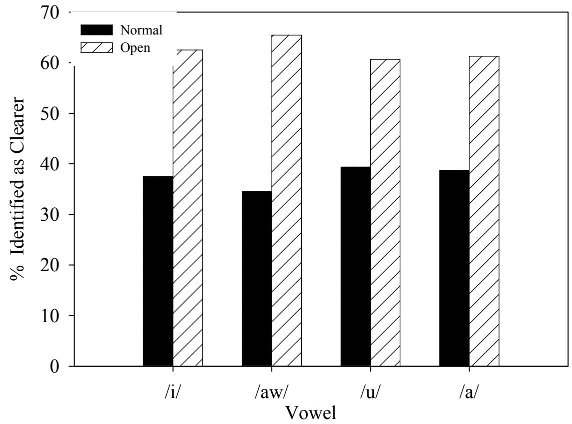
Fixed Length (2)
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.4 - Female Listeners Vowel Clarity Fixed Length



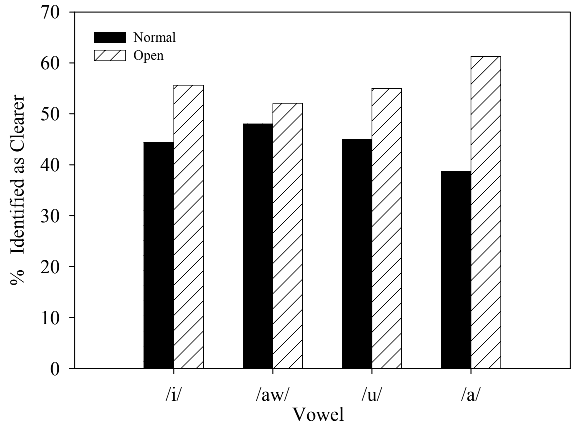
Fixed Length
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.5 - Female Listeners
Vowel Clarity
Variable Length



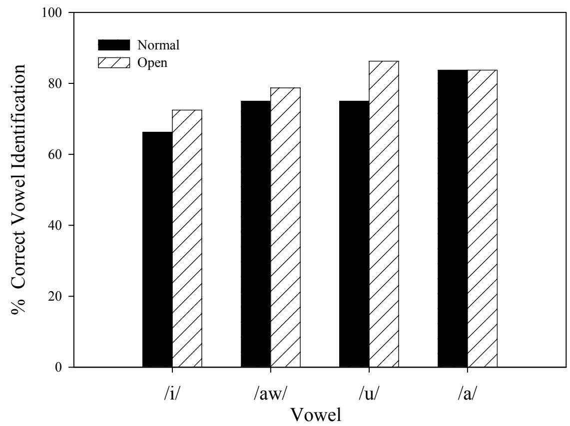
Variable Length
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.6 - Female Listeners
Vowel Clarity
Fixed Length Normalised (65dB)



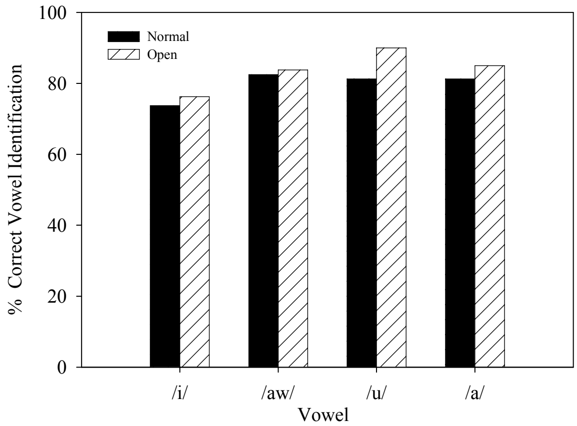
Fixed Length and Normalised (65dB)
Vowels in normal and open jaw posture. Females (n = 20).

Appendix 31.7 - Male Listeners
Vowel Identification
Fixed Length (1)



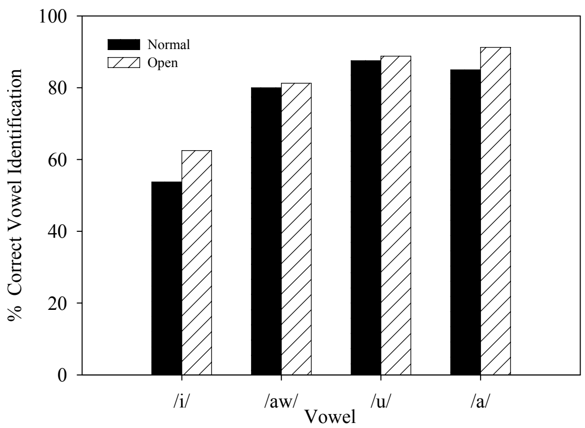
Fixed Length (1)
Vowels in normal and open jaw posture. Males (n = 20).

Appendix 31.8 - Male Listeners
Vowel Identification
Fixed Length Normalised (65dB)



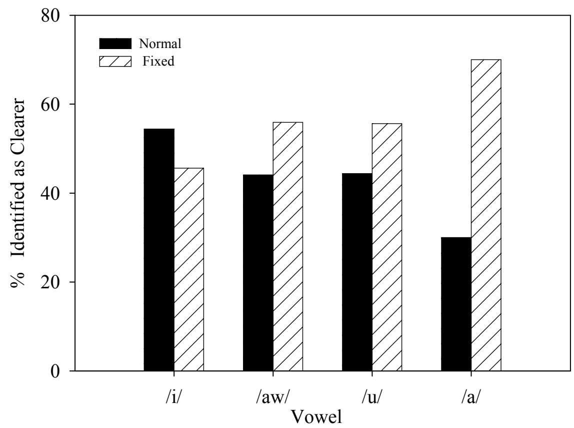
Fixed Length and Normalised (65dB)
Vowels in normal and open jaw posture. Males (n = 20).

Appendix 31.9 - Male Listeners
Vowel Identification
Fixed Length (2)



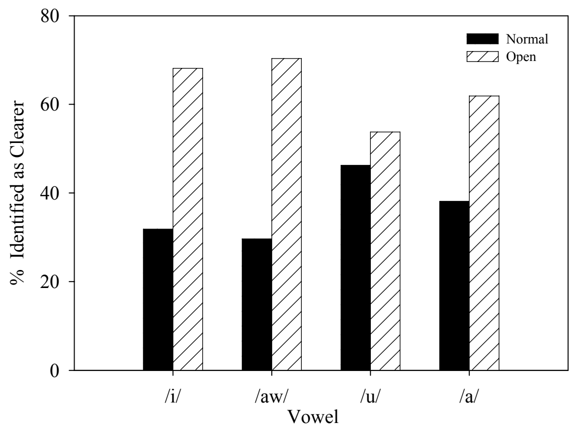
Fixed Length (2)
Vowels in normal and open jaw posture. Males (n = 20)

Appendix 31.10 - Male Listeners
Vowel Clarity
Fixed Length



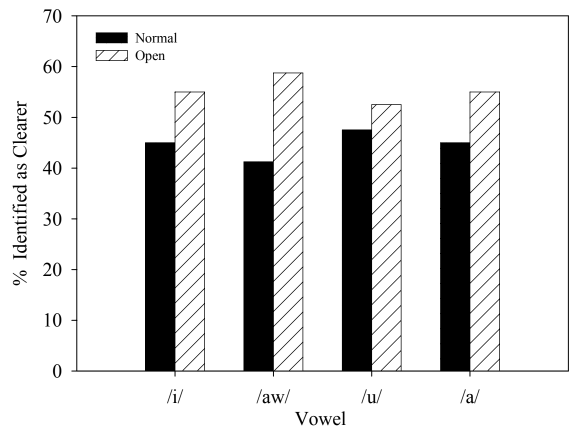
Fixed Length
Vowels in normal and open jaw posture. Males (n = 20).

Appendix 31.11 - Male Listeners
Vowel Clarity
Variable Length



Variable Length
Vowels in normal and open jaw posture. Males (n = 20).

Appendix 31.12 - Male Listeners
Vowel Clarity
Fixed Length Normalised (65dB)



Fixed Length and Normalised (65dB)
Vowels in normal and open jaw posture. Males (n = 20).

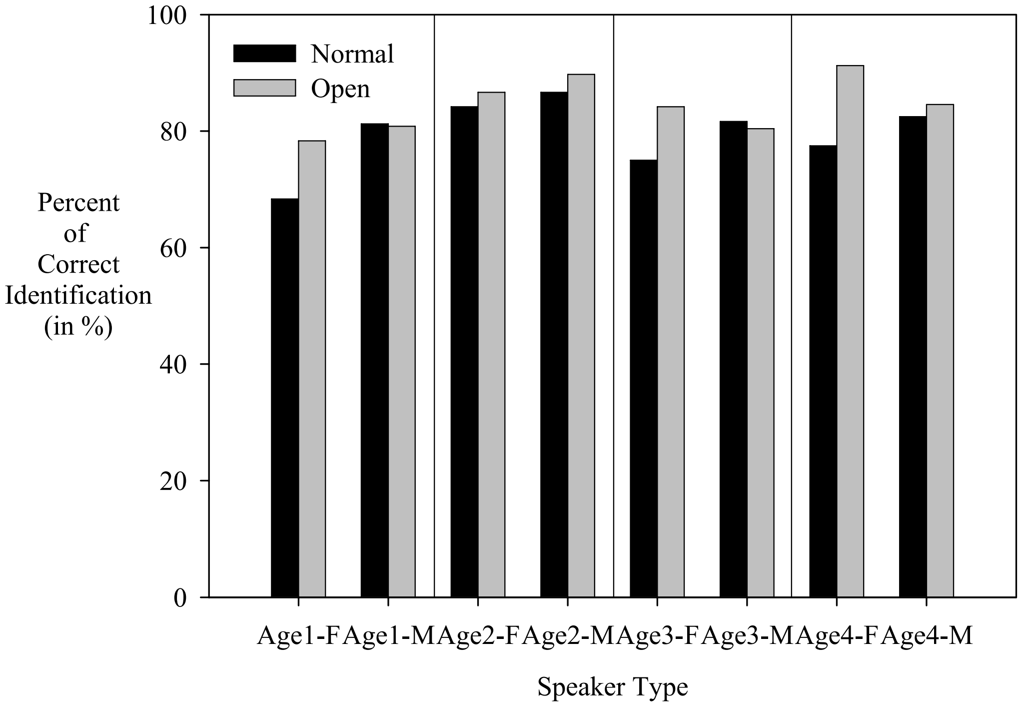
Appendix 32. Listener and Listener's Assigned Stimulus Information

Listener Sorted Code	Age	Gender	Assigned Group	Speaker Information Gender-Age Group (Accent)*
1	18	Female	E	F-4 (NZ), F-2 (US), M-3 (NZ), M-4 (UK)
2	18	Female	F	F-3 (NZ), F-1 (SA), M-2 (NZ), M-4 (NZ)
3	18	Female	H	F-1 (NZ), F-3 (NZ), M-1 (US), M-3 (UK)
4	18	Female	J	F-1 (US), F-2 (US), M-2 (UK), M-3 (UK)
5	19	Female	F	F-3 (NZ), F-1 (SA), M-2 (NZ), M-4 (NZ)
6	**19**	**Female**	**G**	**F-1 (NZ), F-4 (NZ), M-2 (NZ), M-3 (NZ)**
7	20	Female	E	F-4 (NZ), F-2 (US), M-3 (NZ), M-4 (UK)
8	21	Female	C	F-3 (NZ), F-4 (UK), M-1 (US), M-1 (UK)
9	21	Female	D	F-1 (NZ), F-3 (NZ), M-3 (NZ), M-4 (UK)
10	**21**	**Female**	**G**	**F-1 (NZ), F-4 (NZ), M-2 (NZ), M-3 (NZ)**
11	23	Female	J	F-1 (US), F-2 (US), M-2 (UK), M-3 (UK)
12	**24**	**Female**	**B**	**F-2 (NZ), F-4 (NZ), M-1 (NZ), M-2 (NZ)**
13	26	Female	A	F-4 (NZ), F-2 (UK), M-1 (NZ), M-2 (US)
14	**26**	**Female**	**K**	**F-2 (NZ), F-3 (NZ), M-4 (NZ), M-4 (NZ)**
15	27	Female	A	F-4 (NZ), F-2 (UK), M-1 (NZ), M-2 (US)
16	**32**	**Female**	**B**	**F-2 (NZ), F-4 (NZ), M-1 (NZ), M-2 (NZ)**
17	36	Female	D	F-1 (NZ), F-3 (NZ), M-3 (NZ), M-4 (UK)
18	37	Female	H	F-1 (NZ), F-3 (NZ), M-1 (US), M-3 (UK)
19	40	Female	C	F-3 (NZ), F-4 (UK), M-1 (US), M-1 (UK)
20	**42**	**Female**	**K**	**F-2 (NZ), F-3 (NZ), M-4 (NZ), M-4 (NZ)**
21	18	Male	C	F-3 (NZ), F-4 (UK), M-1 (US), M-1 (UK)
22	19	Male	J	F-1 (US), F-2 (US), M-2 (UK), M-3 (UK)
23	19	Male	J	F-1 (US), F-2 (US), M-2 (UK), M-3 (UK)
24	20	Male	F	F-3 (NZ), F-1 (SA), M-2 (NZ), M-4 (NZ)
25	20	Male	F	F-3 (NZ), F-1 (SA), M-2 (NZ), M-4 (NZ)
26	**20**	**Male**	**G**	**F-1 (NZ), F-4 (NZ), M-2 (NZ), M-3 (NZ)**
27	**20**	**Male**	**G**	**F-1 (NZ), F-4 (NZ), M-2 (NZ), M-3 (NZ)**
28	21	Male	C	F-3 (NZ), F-4 (UK), M-1 (US), M-1 (UK)
29	21	Male	E	F-4 (NZ), F-2 (US), M-3 (NZ), M-4 (UK)
30	21	Male	E	F-4 (NZ), F-2 (US), M-3 (NZ), M-4 (UK)
31	**22**	**Male**	**B**	**F-2 (NZ), F-4 (NZ), M-1 (NZ), M-2 (NZ)**
32	22	Male	H	F-1 (NZ), F-3 (NZ), M-1 (US), M-3 (UK)
33	22	Male	H	F-1 (NZ), F-3 (NZ), M-1 (US), M-3 (UK)
34	**23**	**Male**	**B**	**F-2 (NZ), F-4 (NZ), M-1 (NZ), M-2 (NZ)**
35	23	Male	D	F-1 (NZ), F-3 (NZ), M-3 (NZ), M-4 (UK)
36	**24**	**Male**	**K**	**F-2 (NZ), F-3 (NZ), M-4 (NZ), M-4 (NZ)**
37	28	Male	D	F-1 (NZ), F-3 (NZ), M-3 (NZ), M-4 (UK)
38	**30**	**Male**	**K**	**F-2 (NZ), F-3 (NZ), M-4 (NZ), M-4 (NZ)**
39	33	Male	A	F-4 (NZ), F-2 (UK), M-1 (NZ), M-2 (US)
40	47	Male	A	F-4 (NZ), F-2 (UK), M-1 (NZ), M-2 (US)

*Gender: F = female, M = male; Age group: 1 = 35+, 2, = 60+, 3 = 70+, 4 = 80+;
Accent: NZ = New Zealand, US = United States, UK = United Kingdom, SA = South Africa

Appendix 33.

Vowel identification test results: The average percent of correct identification for vowels produced in two jaw postures (normal and open) by female and male speakers at four different age groups (Age 1: 35+, Age 2: 60+, Age 3: 70+, Age 4: 80+). Notation: Age1-F means the speakers are females in the 35+ age group.



Appendix 34. Aging effect as identified by different experimental measures in three analysis protocols.

Note:
"I": indicates that aging results in an increase of the experimental measure
"D": indicates that aging results in a decrease of the experimental measure
"X": indicates mixed results.
"Shaded area": not applicable

	Isolated /a/ at normal pitch	**Sustained /a/ in five tasks (normal, high, low, /ma/, & /ha/)**	**Embedded vowel /a/**	**Embedded vowels**
F0	Female: X Male: I	Female: X Male: I		Female: X Male: I
EGG F0	Male: I	Female: X Male: I	Male: I	Female: D Male: I
%jitter	Female: I	Female: I Male: I		Female: I Male: D
%shimmer	Female: I	Female: I	Males: D	Male: D
SNR	Female: D	Female: D		Male: I
F1		Female: D Male: I		Female: D Male: X
F2	Female: X	Female: X Male: I	Female: X Male: X	Female: X Male: X
H1-H2		Female: X Male: X		
SPL				
VOT 'cars'				Female: X Male: D
VOT 'two'				Male: D
Vowel duration				

Sentence duration				
SQ		Female: X Male: X		Female: X Male: X
OQ		Female: D Male: X		Female: D Male: X
MFR				
Air pressure (in /pa/)				
Air flow (in /pa/)				
LAR (in /pa/)				

Appendix 35. Jaw posture effect as identified by different experimental measures in three analysis protocols.

Note:
"I": indicates that an open jaw posture results in an increase of the experimental measure
"D": indicates that an open jaw posture results in a decrease of the experimental measure
"X": indicates mixed results.
"Shaded area": not applicable

	Isolated /a/ at normal pitch	**Sustained /a/ in five tasks (normal, high, low, /ma/, & /ha/)**	**Embedded vowel /a/**	**Embedded vowels**
F0	Female: I Male: I	Female: I Male: I	Female: I Male: I	Female: I Male: I
EGG F0	Female: I Male: I	Female: I Male: I	Female: I Male (80+): I	Male: I
%jitter	Males: D		Female: D	Female: D Male: D
%shimmer			Female: D Male: X	Female: D Male: D
SNR				Female: I Male: I
F1	Female: I		Female: I Male: I	Male: I (/ɔ/)
F2	Female: D Male: D	Female: D	Female: D	
H1-H2	Female: D	Female: D Male: D		
SPL	Female: I Male: I			
VOT "cars"				Female: I Male: I

VOT "two"				Male: I
Vowel duration			Female: I Male: I	For: /i, ɔ, u, a/ Female: I Male: I
Sentence duration				Female: I Male: I
SQ				
OQ	Female: I			
MFR	Female: I Male: I			
Air pressure (in /pa/)	Female: I			
Air flow (in /pa/)	Female: I			
LAR (in /pa/)				

Appendix 36. Results from three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVAs performed on the acoustic measures (F0, %jitter, %shimmer, SNR, F1, F2, and H1-H2 amplitude difference) for the vowel /a/ sustained in a one-syllable task (normal, high, and low pitch and /m/ and /h/-initiated). Number of participants: females = 56 and males = 29, n = the number of tokens (2 posture 5 tasks x nbr of participants) submitted for analysis.

F0

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 13.438, **p < 0.001****	F(3, 250) = 28.298, **p < 0.001****
Posture	F(1, 520) = 16.745, **p < 0.001****	F(1, 250) = 10.735, **p = 0.001***
Task	F(4, 520) = 123.920, **p < 0.001****	F(4, 250) = 67.459, **p < 0.001****
Age x Posture	F(3, 520) = 0.316, p = 0.814	F(3, 250) = 1.234, p = 0.298
Age x Task	F(12, 520) = 0.571, p = 0.866	F(12, 250) = 0.163, p = 0.999
Posture x Task	F(4, 520) = 0.718, p = 0.580	F(4, 250) = 0.205, p = 0.936
Age x Posture x Task	F(12, 520) = 0.126, p = 1.000	F(12, 250) = 0.082, p = 1.000

%jitter

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 21.823, **p < 0.001****	F(3, 250) = 2.787, **p = 0.041***
Posture	F(1, 520) = 0.833, p = 0.362	F(1, 250) = 1.940, p = 0.165
Task	F(4, 520) = 4.976, **p < 0.001****	F(4, 250) = 7.090, **p < 0.001****
Age x Posture	F(3, 520) = 0.586, p = 0.625	F(3, 250) = 0.091, p = 0.965
Age x Task	F(12, 520) = 0.909, p = 0.538	F(12, 250) = 0.860, p = 0.589
Posture x Task	F(4, 520) = 0.696, p = 0.595	F(4, 250) = 0.113, p = 0.978
Age x Posture x Task	F(12, 520) = 0.390, p = 0.967	F(12, 250) = 0.549, p = 0.881

%shimmer

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 17.441, **p < 0.001****	F(3, 250) = 1.6070, p = 0.188
Posture	F(1, 520) = 0.018, p = 0.894	F(1, 250) = 0.0001, p = 9.992
Task	F(4, 520) = 3.834, **p = 0.004***	F(4, 250) = 7.2080, **p < 0.001****
Age x Posture	F(3, 520) = 0.302, p = 0.824	F(3, 250) = 0.2000, p = 0.896
Age x Task	F(12, 520) = 0.733, p = 0.719	F(12, 250) = 0.6450, p = 0.803
Posture x Task	F(4, 520) = 0.598, p = 0.664	F(4, 250) = 0.3120, p = 0.870
Age x Posture x Task	F(12, 520) = 0.462, p = 0.936	F(12, 250) = 0.6940, p = 0.756

*Significant at 0.05 level **Significant at 0.005 level

SNR

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 20.900, **p < 0.001****	F(3, 250) = 1.745, p = 0.158
Posture	F(1, 520) = 0.057, p = 0.812	F(1, 250) = 0.483, p = 0.488
Task	F(4, 520) = 11.118, **p < 0.001****	F(4, 250) = 22.147, **p < 0.001****
Age x Posture	F(3, 520) = 0.494, p = 0.686	F(3, 250) = 0.479, p = 0.697
Age x Task	F(12, 520) = 0.896, p = 0.551	F(12, 250) = 1.292, p = 0.223
Posture x Task	F(4, 520) = 0.164, p = 0.957	F(4, 250) = 0.089, p = 0.986
Age x Posture x Task	F(12, 520) = 0.109, p = 1.000	F(12, 250) = 0.242, p = 0.996

F1

Effects	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 5.818, **p < 0.001****	F(3, 250) = 11.149, **p < 0.001****
Posture	F(1, 520) = 1.724, p = 0.190	F(1, 250) = 0.426, p = 0.514
Task	F(4, 520) = 4.326, **p = 0.002***	F(4, 250) = 5.904, **p < 0.001****
Age x Posture	F(3, 520) = 0.560, p = 0.641	F(3, 250) = 1.120, p = 0.341
Age x Task	F(12, 520) = 1.092, p = 0.365	F(12, 250) = 0.377, p = 0.971
Posture x Task	F(4, 520) = 0.437, p = 0.782	F(4, 250) = 0.181, p = 0.948
Age x Posture x Task	F(12, 520) = 0.205, p = 0.998	F(12, 250) = 0.168, p = 0.999

F2

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 21.198, **p < 0.001****	F(3, 250) = 10.556, **p < 0.001****
Posture	F(1, 520) = 14.694, **p < 0.001****	F(1, 250) = 3.332, p = 0.069
Task	F(4, 520) = 4.732, **p < 0.001****	F(4, 250) = 5.949, **p < 0.001****
Age x Posture	F(3, 520) = 0.014, p = 0.998	F(3, 250) = 0.287, p = 0.834
Age x Task	F(12, 520) = 0.650, p = 0.799	F(12, 250) = 0.295, p = 0.990
Posture x Task	F(4, 520) = 0.398, p = 0.810	F(4, 250) = 0.205, p = 0.935
Age x Posture x Task	F(12, 520) = 0.227, p = 0.997	F(12, 250) = 0.228, p = 0.997

H1-H2 Amplitude Difference

Effect	Females (n = 560)	Males (n = 290)
Age	F(3, 520) = 10.523, **p < 0.001****	F(3, 250) = 12.671, **p < 0.001****
Posture	F(1, 520) = 10.309, **p = 0.001***	F(1, 250) = 5.003, **p = 0.026***
Task	F(4, 520) = 4.955, **p < 0.001****	F(4, 250) = 8.699, **p < 0.001****
Age x Posture	F(3, 520) = 0.429, p = 0.733	F(3, 250) = 0.108, p = 0.955
Age x Task	F(12, 520) = 0.385, p = 0.969	F(12, 250) = 0.361, p = 0.975
Posture x Task	F(4, 520) = 0.051, p = 0.995	F(4, 250) = 0.036, p = 0.997
Age x Posture x Task	F(12, 520) = 0.170, p = 0.999	F(12, 250) = 0.261. p = 0.994

*Significant at 0.05 level **Significant at 0.005 level

Appendix 37. Bar charts of the three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVA results for the vowel /a/ sustained in a one-syllable task (normal, high, and low pitch and /m/ and /h/-initiated) for females (n = 56) and males (n = 29).

Notes:
(1) Groups significantly different are marked with different letters.
(2) "*" indicates a significant difference between the paired groups.
(3) "n" indicates the number of participants in each age group.

Figure 37.1 - Females F0
Age effect

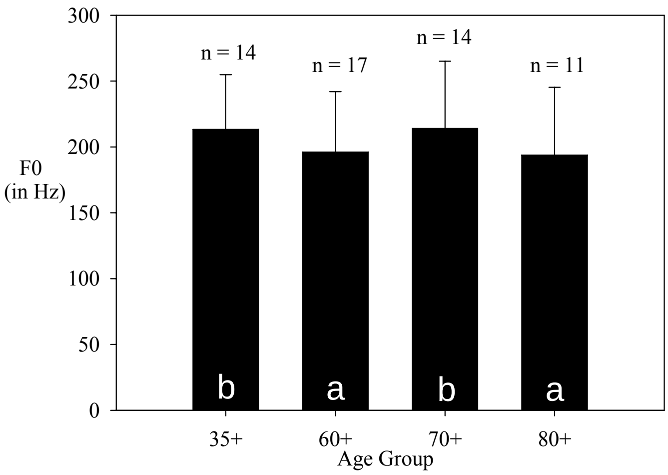


Figure 37.2 - Males F0
Age effect

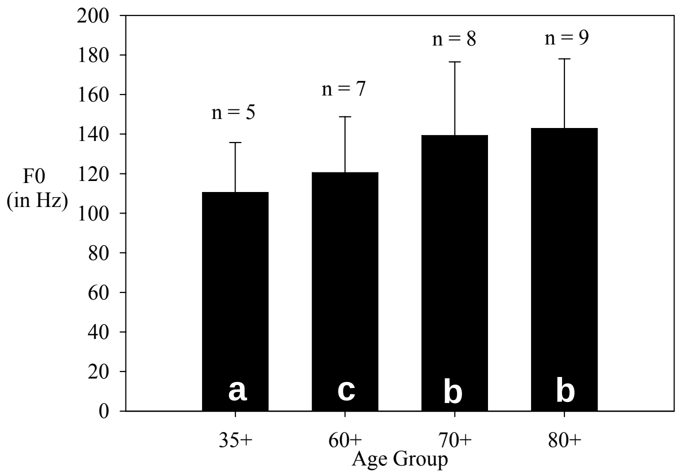


Figure 37.3 - Females and Males F0
Posture Effects

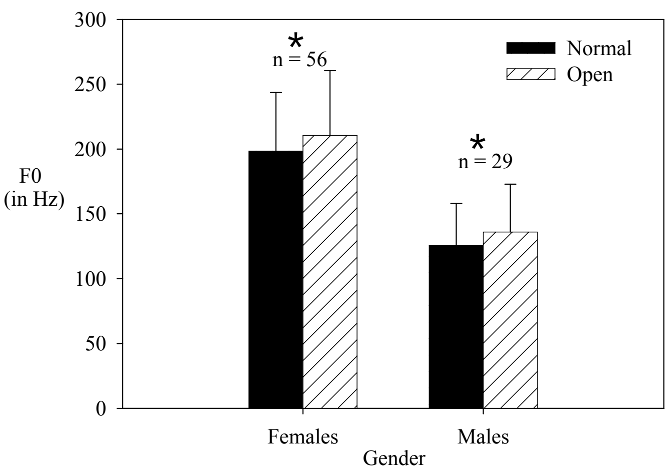


Figure 37.4 – Females F0
Task Effects

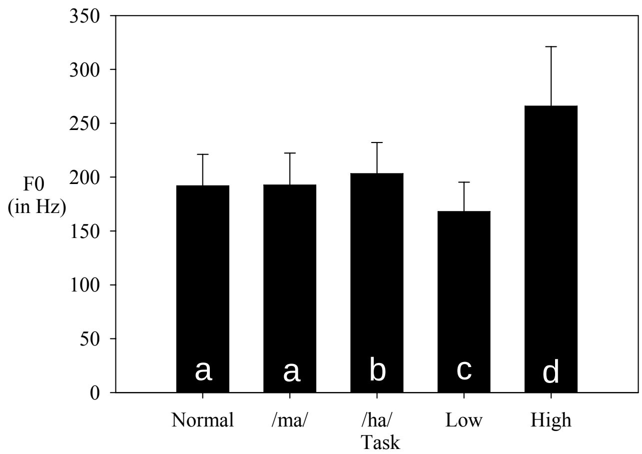


Figure 37.5 – Males F0
Task Effect

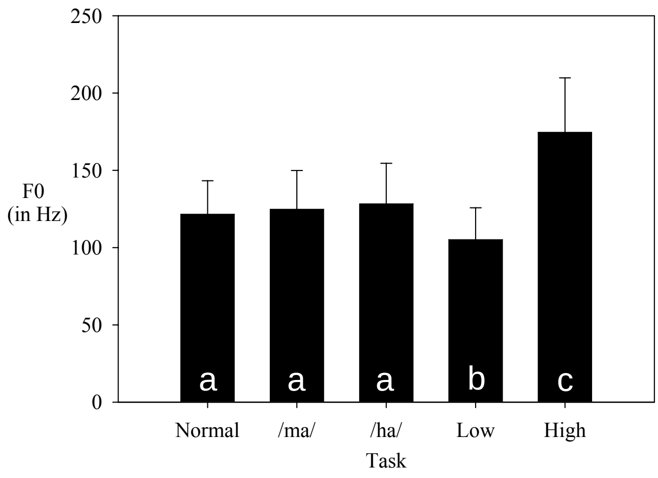


Figure 37.6 - Females %jitter
Age effect

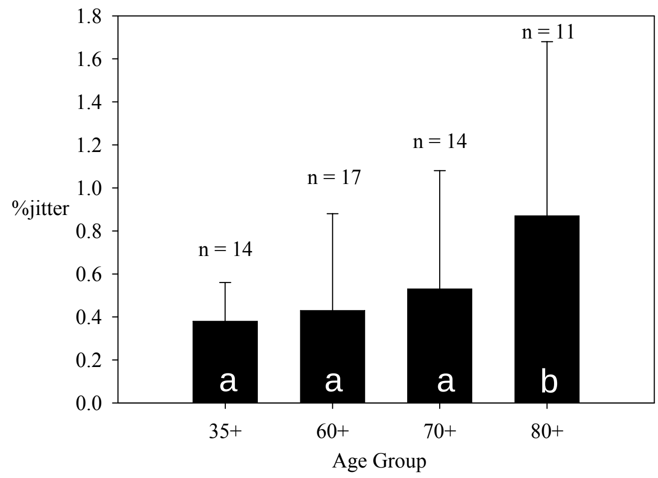


Figure 37.7 - Males %jitter
Age effect

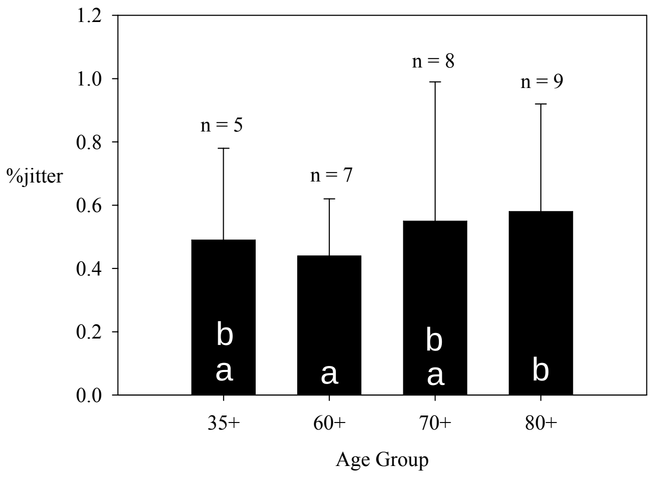


Figure 37.8 - Females %jitter
Task Effect

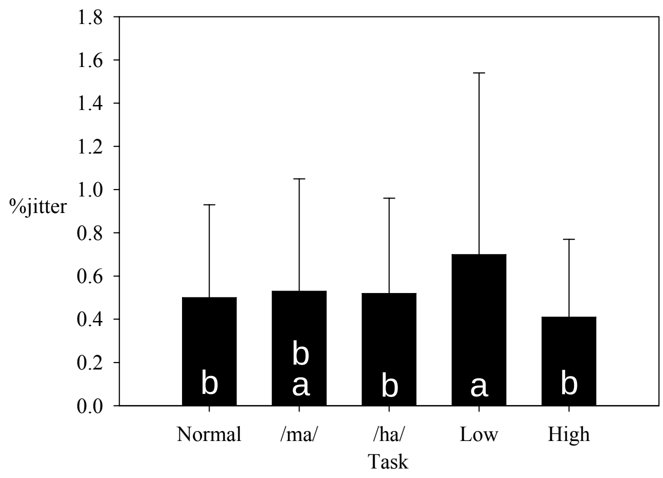


Figure 37.9 - Males %jitter
Task Effect

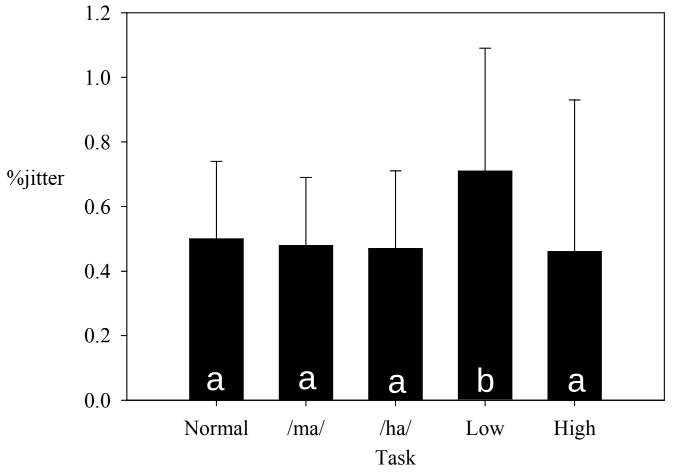


Figure 37.10 - Females %shimmer
Age effect

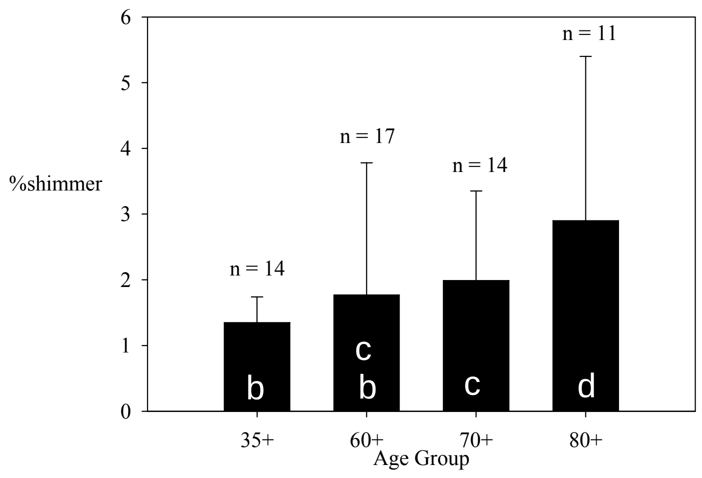


Figure 37.11 - Females %shimmer
Task Effect

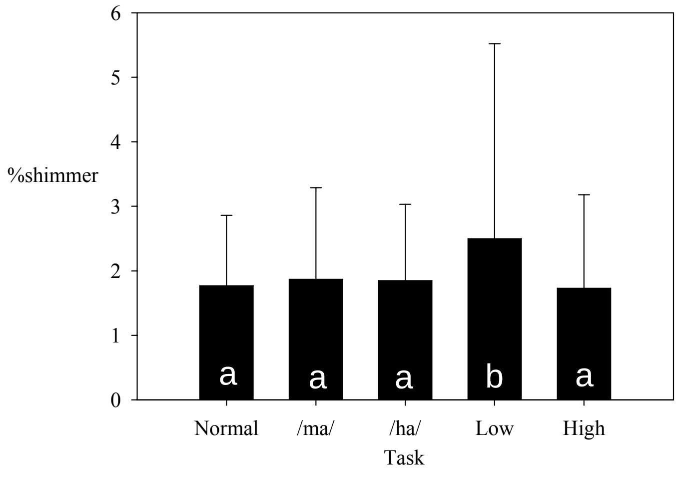


Figure 37.12 - Males %shimmer
Task Effect

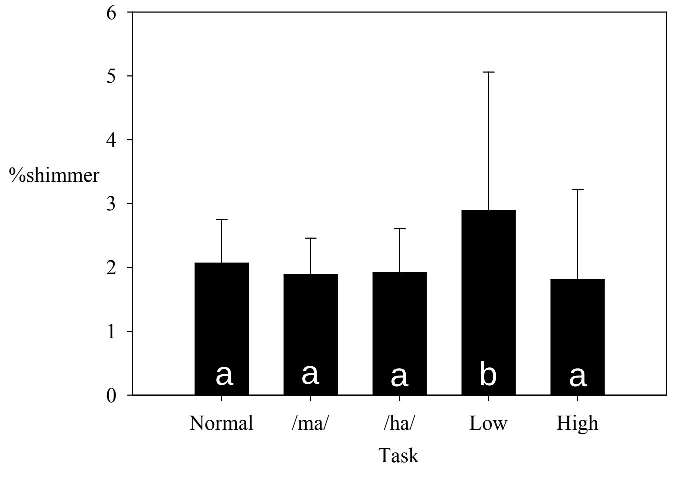


Figure 37.13 - Females SNR
Age effect

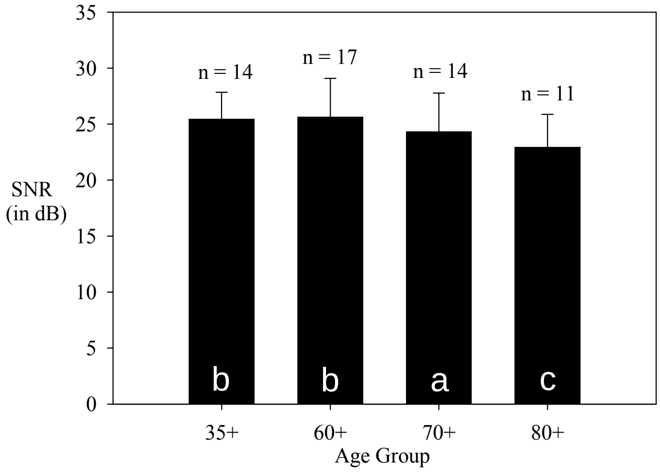


Figure 37.14 - Females SNR
Task Effect

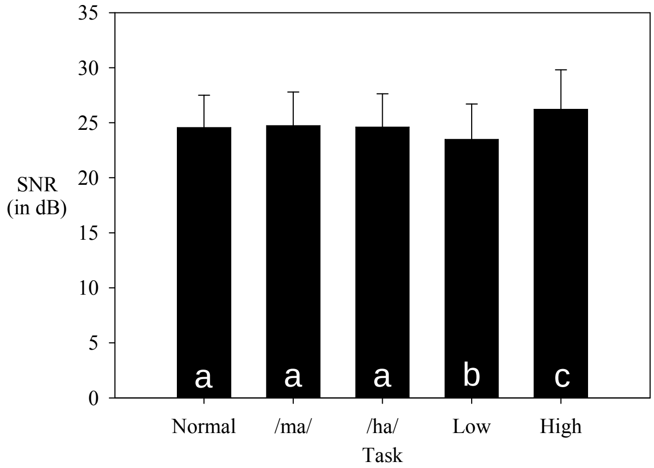


Figure 37.15 - Males SNR
Task Effect

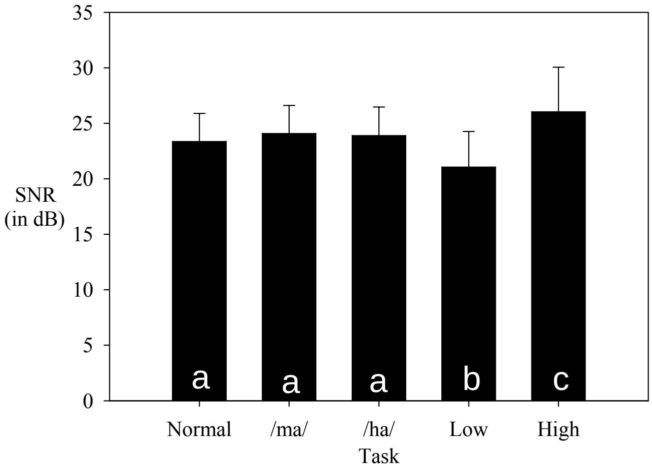


Figure 37.16 – Females F1
Age effect

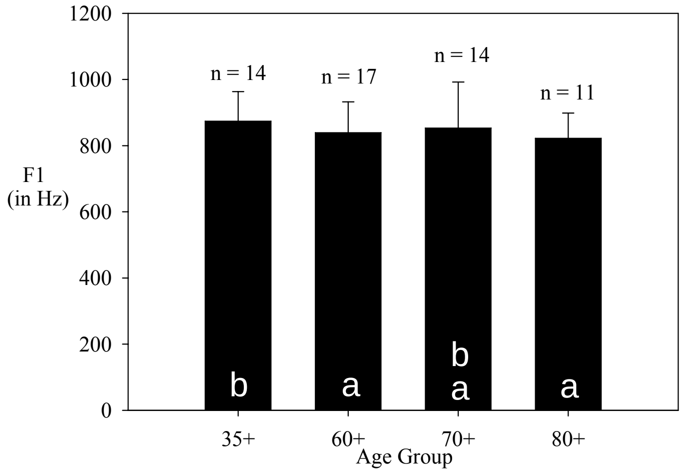


Figure 37.17 – Males F1
Age effect

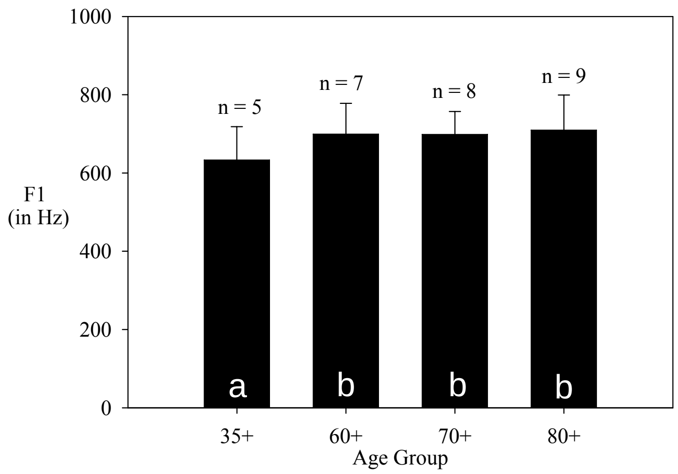


Figure 37.18 - Females F1
Task Effect

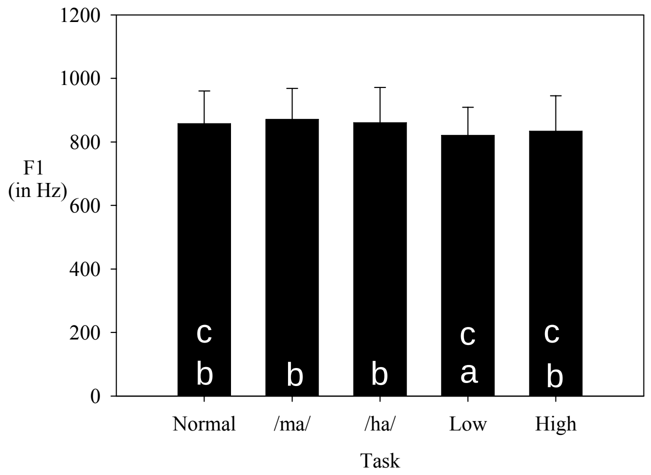


Figure 37.19 - Males F1
Task Effect

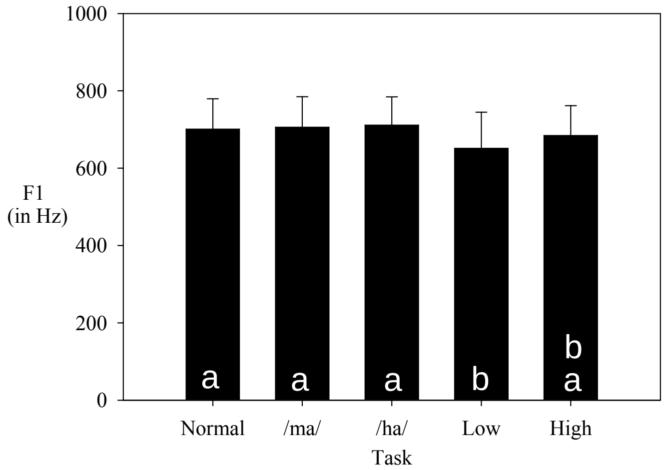


Figure 37.20 - Females F2
Age effect

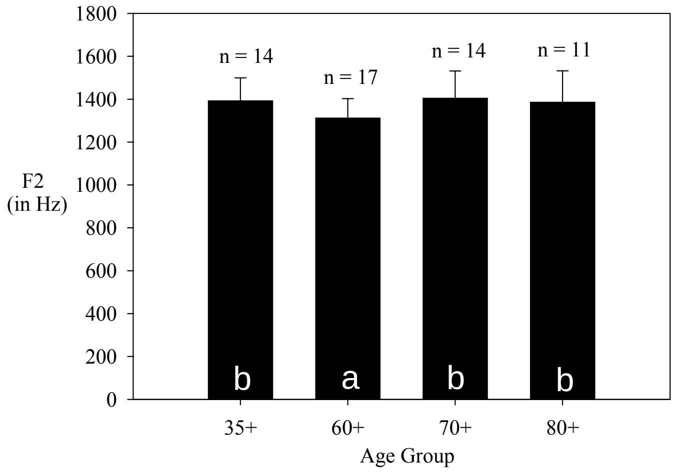


Figure 37.21 - Males F2
Age effect

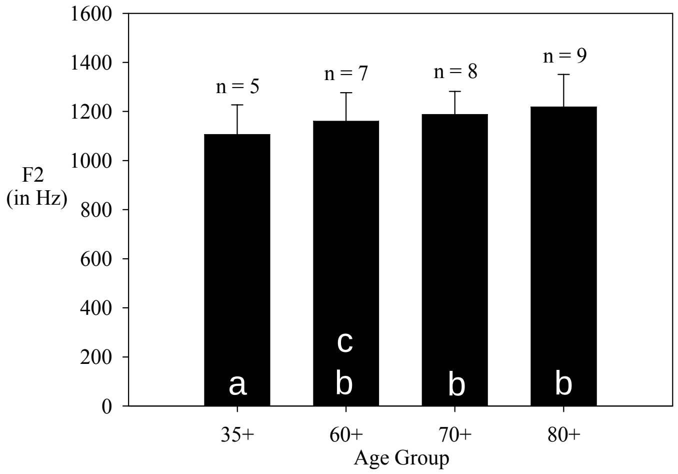


Figure 37.22 - Females F2
Posture Effect

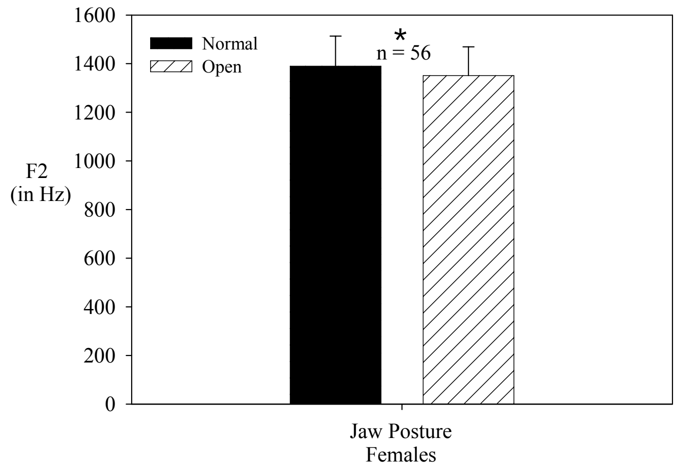


Figure 37.23 - Females F2
Task Effect

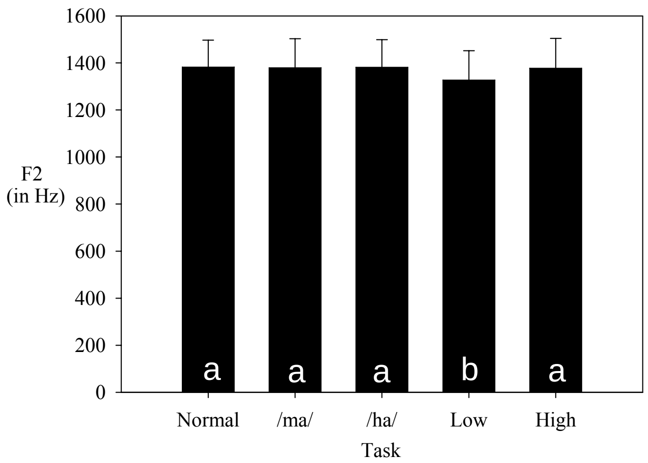


Figure 37.24 - Males F2
Task Effect

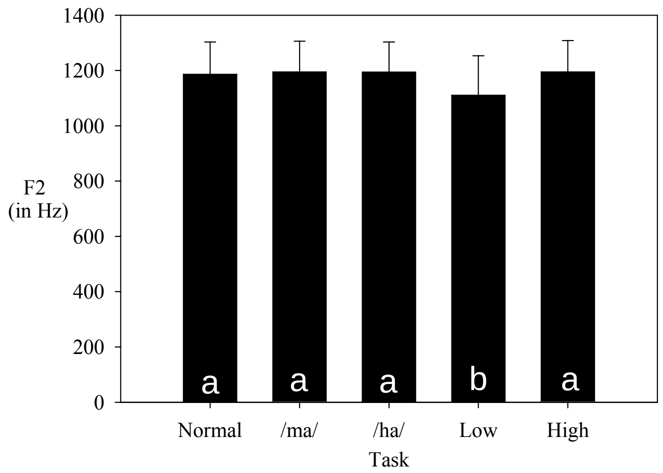


Figure 37.25 - Females H1-H2
Age effect

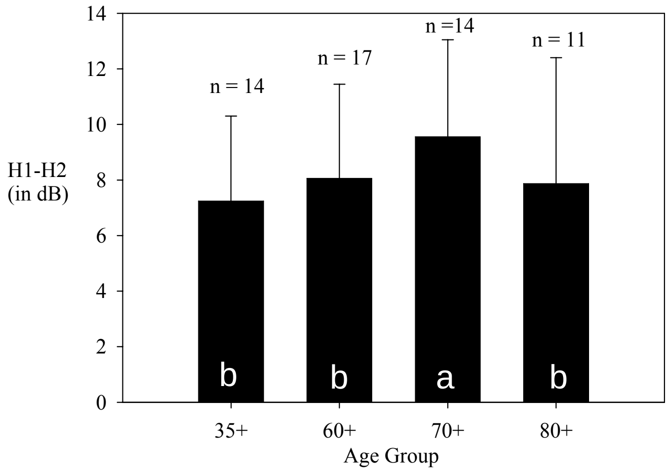


Figure 37.26 - Males H1-H2
Age effect

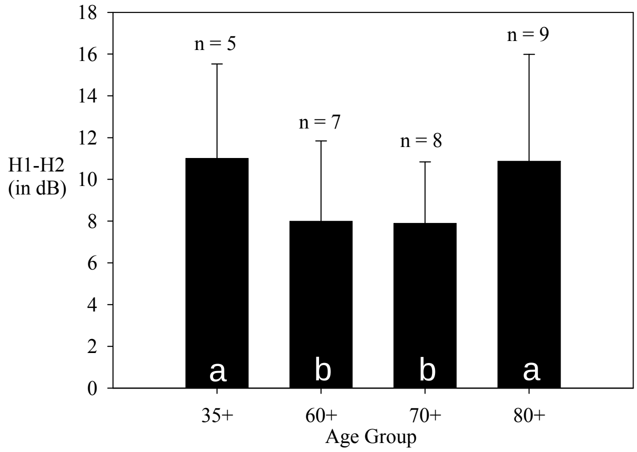


Figure 37.27 - Females and Males H1-H2
Posture Effect

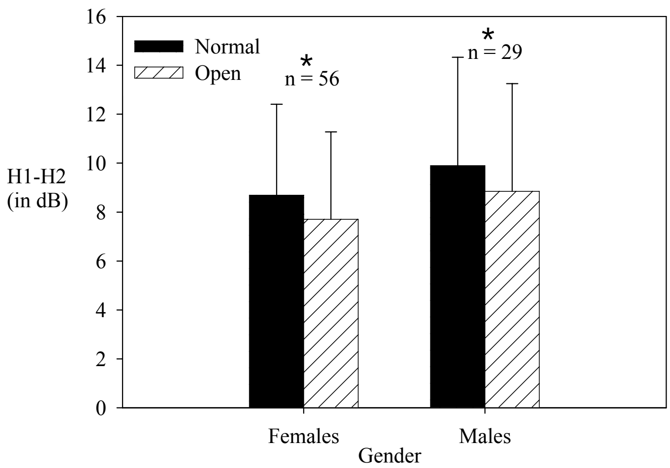


Figure 37.28 - Females H1-H2
Task Effect

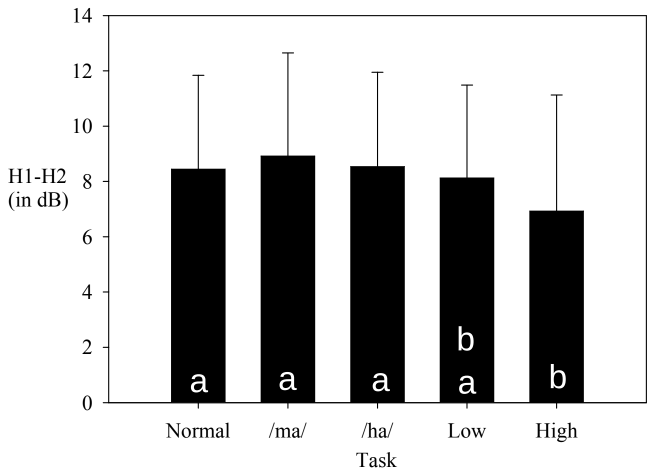
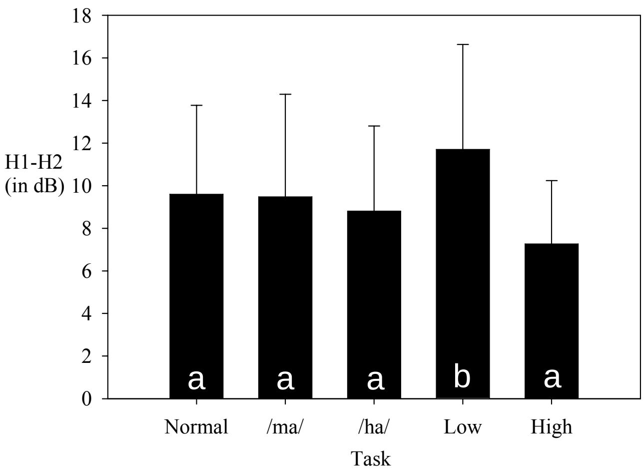


Figure 37.29 - Males H1-H2
Task Effect



Appendix 38 Results from three-way (2 jaw postures X 4 age groups X 4 vowels) ANOVAs performed on the acoustic measures (F0, %jitter, %shimmer, SNR, F1, and F2) for the embedded vowels /i, ɔ, u, a/ produced in a sentence "We saw two cars.". Number of participants: females = 56 and males = 29, n = the number of tokens (2 posture 4 vowels x the number of participants) submitted for analysis.

F0

Effect	Females (n = 448)	Males (n = 232)
Age	F(3, 416) = 5.607, **p < 0.001****	F(3, 200) = 25.622, **p < 0.001****
Posture	F(1, 416) = 8.000, **p = 0.005***	F(1, 200) = 6.514, **p = 0.001***
Vowel	F(3, 416) = 43.467, p **= 0.005***	F(3, 200) = 4.468, **p = 0.005***
Age x Posture	F(3, 416) = 0.695, p = 0.555	F(3, 200) = 0.620, p = 0.603
Age x Vowel	F(9, 416) = 1.314, p = 0.227	F(9, 200) = 0.461, p = 0.899
Posture x Vowel	F(3, 416) = 0.036, p = 0.991	F(3, 200) = 0.071, p = 0.976
Age x Posture x Vowel	F(9, 416) = 0.187, p = 0.995	F(9, 200) = 0.130, p = 0.999

%jitter

Effect	Females (n = 456)	Males (n = 232)
Age	F(3, 416) = 3.460, **p = 0.016***	F(3, 200) = 3.378, **p = 0.019***
Posture	F(1, 416) = 12.484, **p < 0.001****	F(1, 200) = 4.385, **p = 0.038***
Vowel	F(3, 416) = 32.607, **p < 0.001****	F(3, 200) = 12.512, **p < 0.001****
Age x Posture	F(3, 416) = 0.207, p = 0.892	F(3, 200) = 0.604, p = 0.613
Age x Vowel	F(9, 416) = 0.712, p = 0.698	F(9, 200) = 0.418, p = 0.924
Posture x Vowel	F(3, 416) = 0.697, p = 0.554	F(3, 200) = 0.136, p = 0.939
Age x Posture x Vowel	F(9, 416) = 0.397, p = 0.936	F(9, 200) = 0.354, p = 0.955

%shimmer

Effect	Females (n = 456)	Males (n = 232)
Age	F(3, 416) = 2.169, p = 0.091	F(3,200) = 6.916, **p < 0.001****
Posture	F(1, 416) = 10.874, **p = 0.001***	F(1,200) = 4.265, **p = 0.040***
Vowel	F(3, 416) = 7.230, **p < 0.001****	F(3,200) = 7.214, **p < 0.001****
Age x Posture	F(3, 416) = 0.081, p = 0.971	F(3,200) = 1.448, p = 0.230
Age x Vowel	F(9, 416) = 1.293, p = 0.238	F(9,200) = 0.814, p = 0.604
Posture x Vowel	F(3, 416) = 0.260, p = 0.854	F(3,200) = 0.498, p = 0.684
Age x Posture x Vowel	F(9, 416) = 0.265, p = 0.984	F(9,200) = 0.232, p = 0.990

SNR

Effect	Females (n = 456)	Males (n = 232)
Age	F(3, 416) = 2.228, p = 0.084	F(3,200) = 6.960, **p < 0.001****
Posture	F(1, 416) = 12.856, **p < 0.001****	F(1,200) = 6.185, **p = 0.014***
Vowel	F(3, 416) = 92.268, **p < 0.001****	F(3,200) = 48.154, **p < 0.001****
Age x Posture	F(3, 416) = 0.257, p = 0.856	F(3,200) = 0.315, p = 0.608
Age x Vowel	F(9, 416) = 1.661, p = 0.096	F(9,200) = 1.036, p = 0.412
Posture x Vowel	F(3, 416) = 1.417, p = 0.237	F(3,200) = 0.557, p = 0.644
Age x Posture x Vowel	F(9, 416) = 0.258, p = 0.985	F(9,200) = 0.210, p = 0.993

F1

Effect	Females (n = 456)	Males (n = 232)
Age	F(3, 416) = 4.470, **p = 0.004***	F(3,200) = 1.480, p = 0.221
Posture	F(1, 416) = 1.605, p = 0.206	F(1,200) = 5.263, **p = 0.023***
Vowel	F(3, 416) = 920.586, **p < 0.001****	F(3,200) = 411.840, **p < 0.001****
Age x Posture	F(3, 416) = 0.004, p = 1.000	F(3,200) = 0.201, p = 0.896
Age x Vowel	F(9, 416) = 1.408, p = 0.182	F(9,200) = 2.359, **p = 0.015***
Posture x Vowel	F(3, 416) = 3.562, **p = 0.014***	F(3,200) = 3.150, **p = 0.026***
Age x Posture x Vowel	F(9, 416) = 0.151, p = 0.998	F(9,200) = 0.628, p = 0.772

F2

Effect	Females (n = 456)	Males (n = 232)
Age	F(3, 416) = 1.343, p = 0.260	F(3,200) = 1.031, p = 0.380
Posture	F(1, 416) = 4.701, **p = 0.031***	F(1,200) = 2.792, p = 0.096
Vowel	F(3, 416) = 1307.880, **p < 0.001****	F(3,200) = 412.088, **p < 0.001****
Age x Posture	F(3, 416) = 0.172, p = 0.915	F(3,200) = 0.453, p = 0.715
Age x Vowel	F(9, 416) = 2.422, **p = 0.011***	F(9,200) = 2.092, **p = 0.032***
Posture x Vowel	F(3, 416) = 7.661, **p < 0.001****	F(3,200) = 1.199, p = 0.311
Age x Posture x Vowel	F(9, 416) = 0.0987, p = 1.000	F(9,200) = 0.225, p = 0.991

*Significant at 0.05 level   **Significant at 0.005 level

Appendix 39. Bar charts of three-way (2 jaw postures X 4 age groups X 4 vowels) ANOVA results for the four embedded vowels /i, ɔ, u, a/ in normal pitch from the sentence "We saw two cars." for females (n = 56) and males (n = 29).

Notes:
(1) The vowel /ɔ/ is written as "aw" in the following graphs.
(2) Groups significantly different are marked with different letters.
(3) "*" indicates a significant difference between the paired groups.
(4) "n" indicates the number of participants in each age group.

Figure 39.1 - Females F0
Age effect

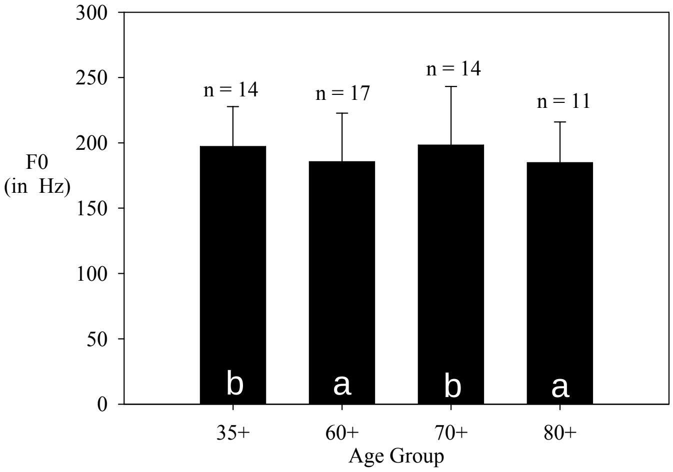


Figure 39.2 - Males F0
Age effect

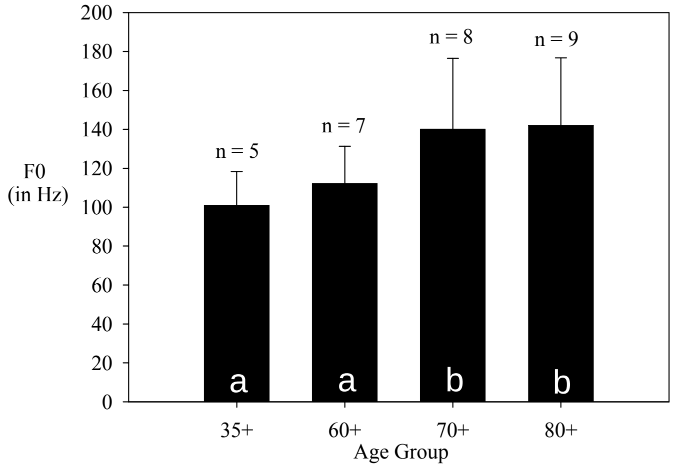


Figure 39.3 - Females and Males F0
Posture Effect

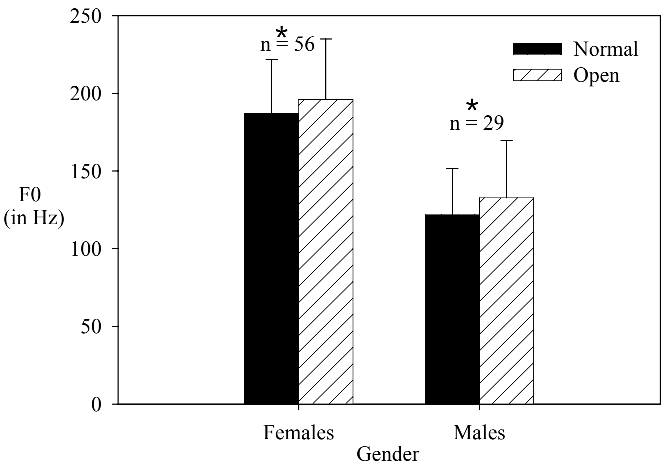


Figure 39.4 - - Females F0
Vowel Effect

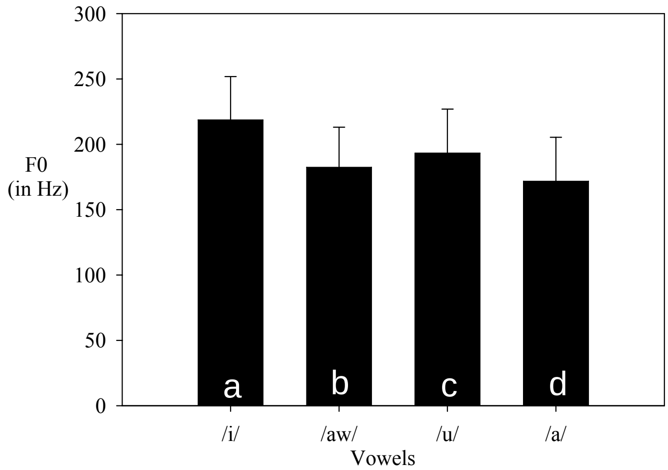


Figure 39.5 Males F0
Vowel Effect

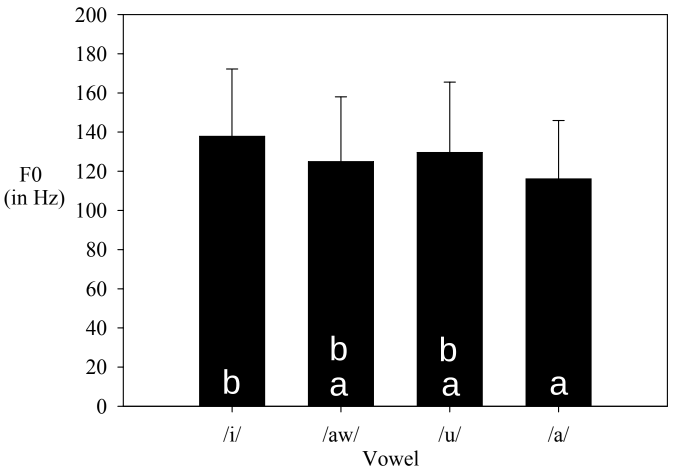


Figure 39.6 - Females %jitter
Age effect

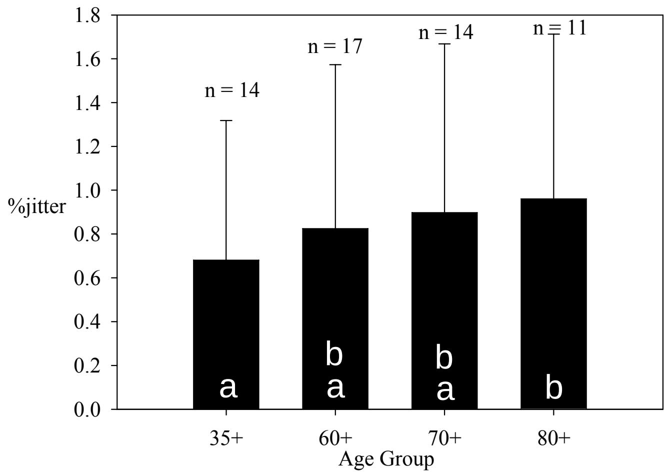


Figure 39.7 - Males %jitter
Age effect

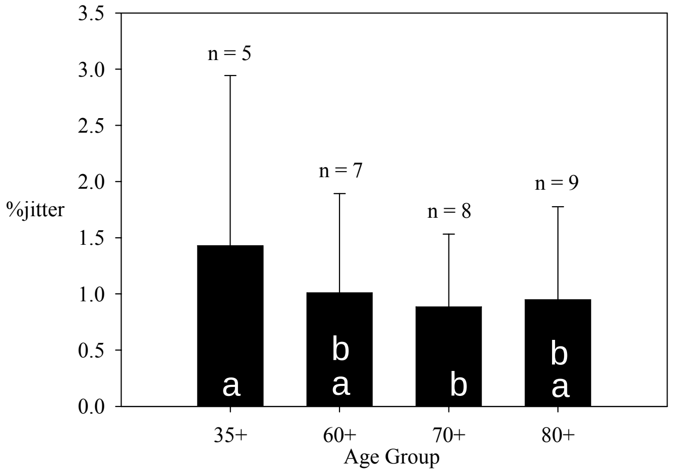


Figure 39.8 - Females and Males %jitter
Posture Effect

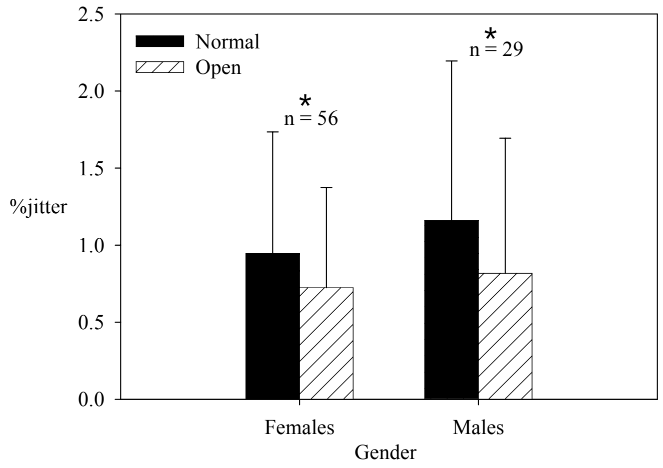


Figure 39.9 - Females %jitter
Vowel Effect

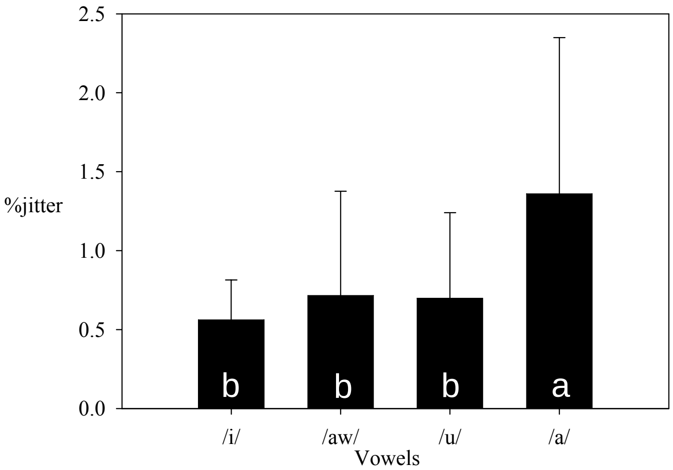


Figure 39.10 - Males %jitter
Vowel Effect

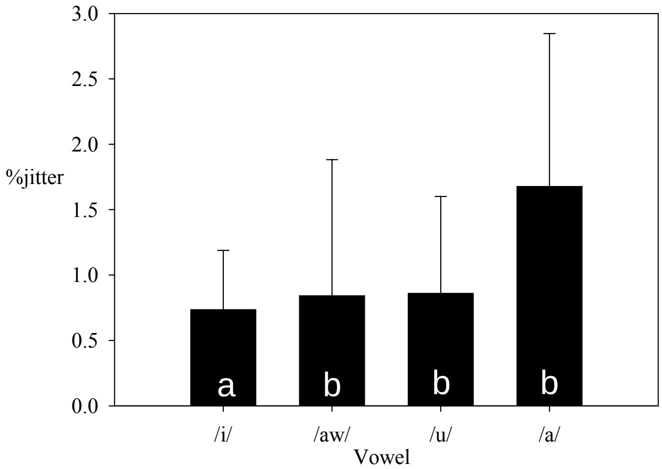


Figure 39.11 - Males %shimmer
Age effect

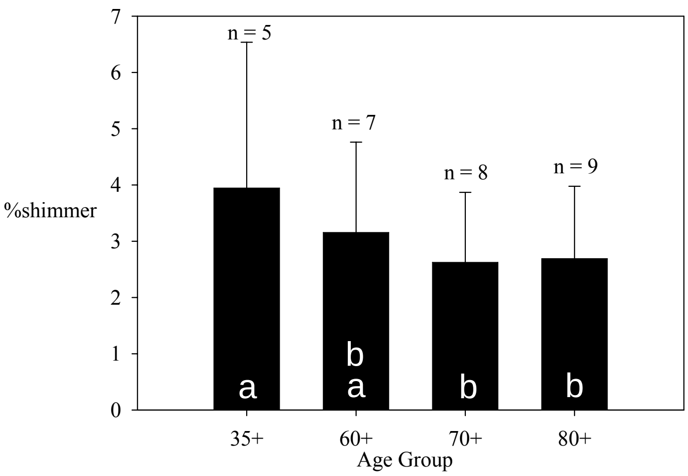


Figure 39.12 - Females and Males %shimmer
Posture Effect

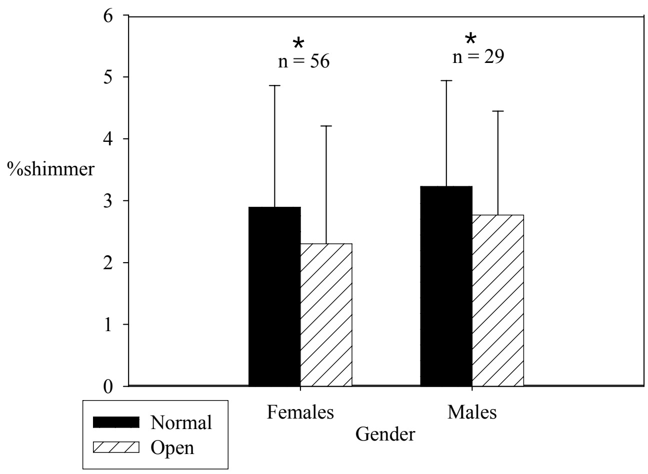


Figure 39.13 - Females %shimmer
Vowel Effect

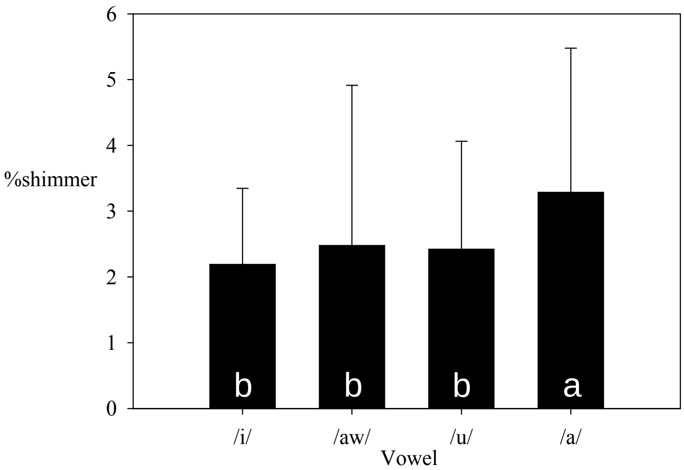


Figure 39.14 - Males %shimmer
Vowel Effect

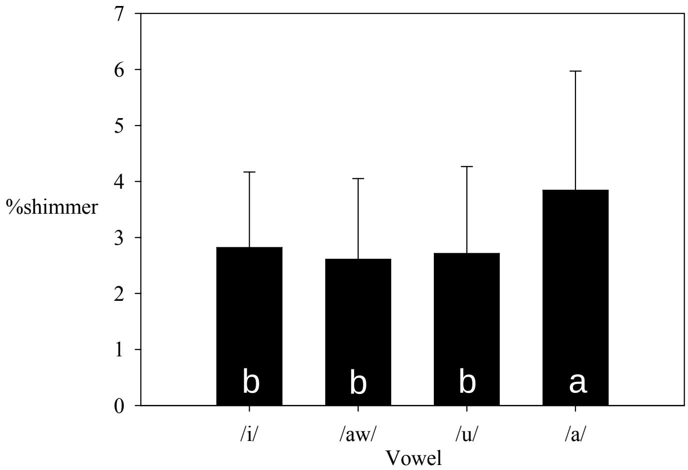


Figure 39.15 - Males SNR
Age effect

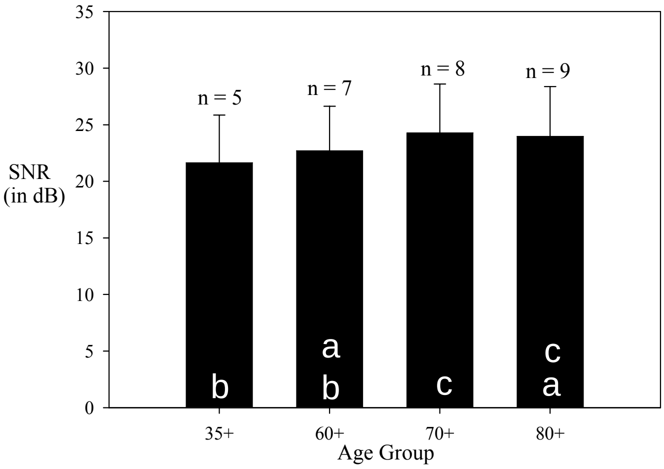


Figure 39.16 - Females and Males SNR
Posture Effect

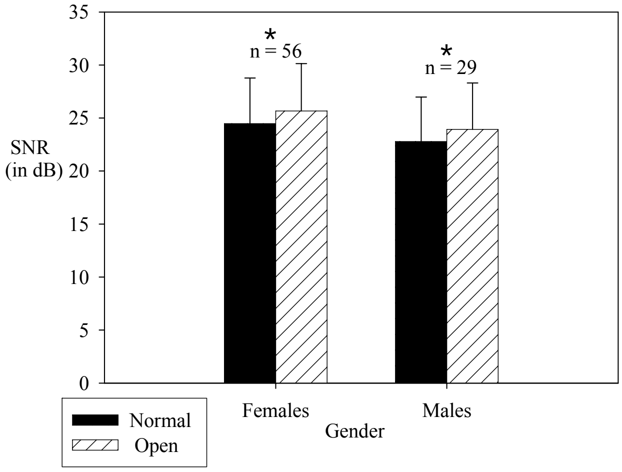


Figure 39.17 - Females SNR
Vowel Effect

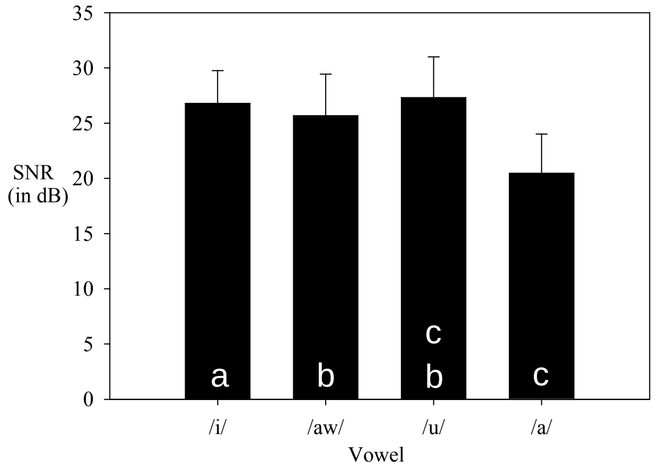


Figure 39.18 - Males SNR
Vowel Effect

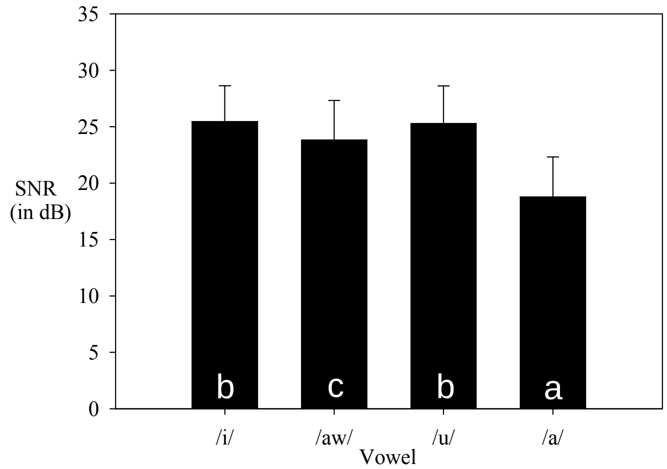


Figure 39.19 - Females F1
Age effect

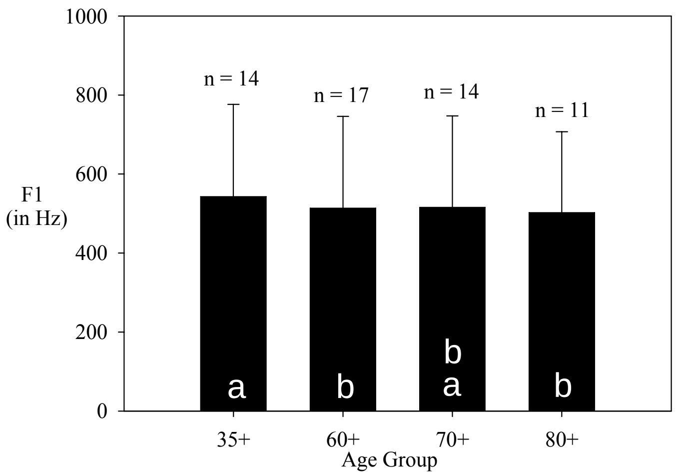


Figure 39.20 - Females F1
Posture x Vowel Interaction Effect

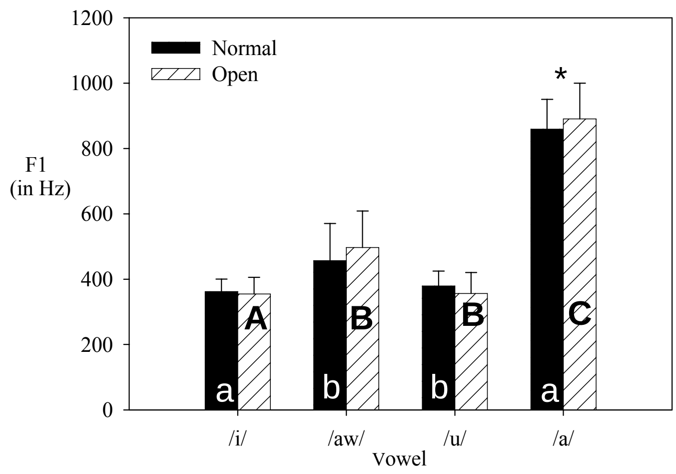


Figure 39.21 - Males F1
Posture x Vowel Interaction Effect

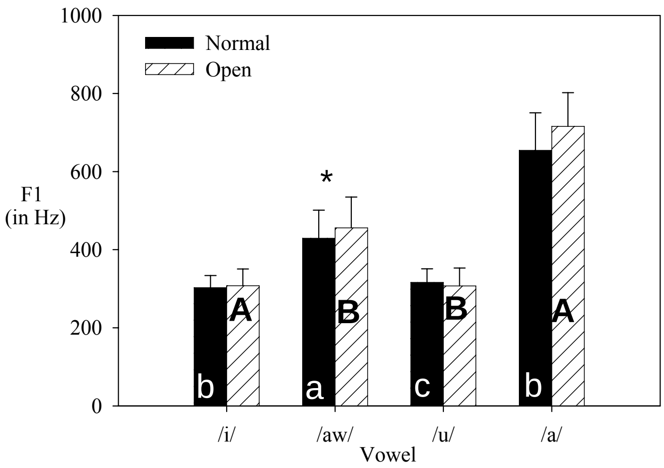


Figure 39.22 - Males F1
Age x Vowel Interaction Effect

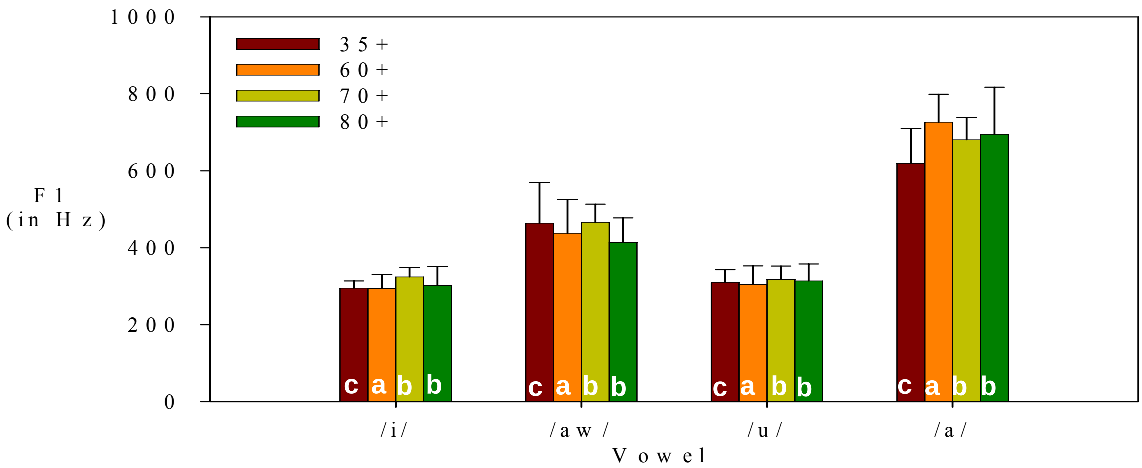


Figure 39.23 - Females F2
Age x Vowel Interaction Effect

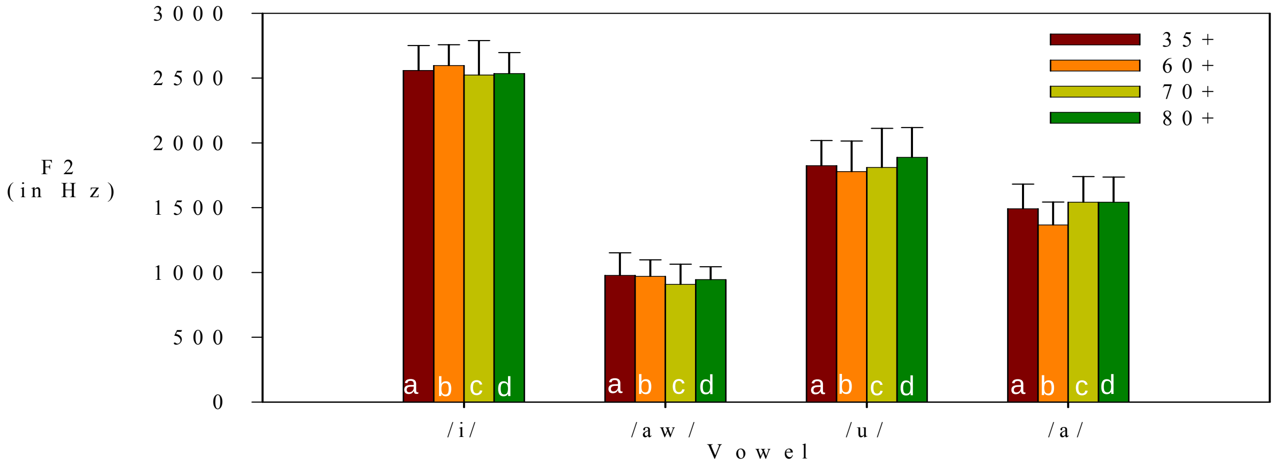
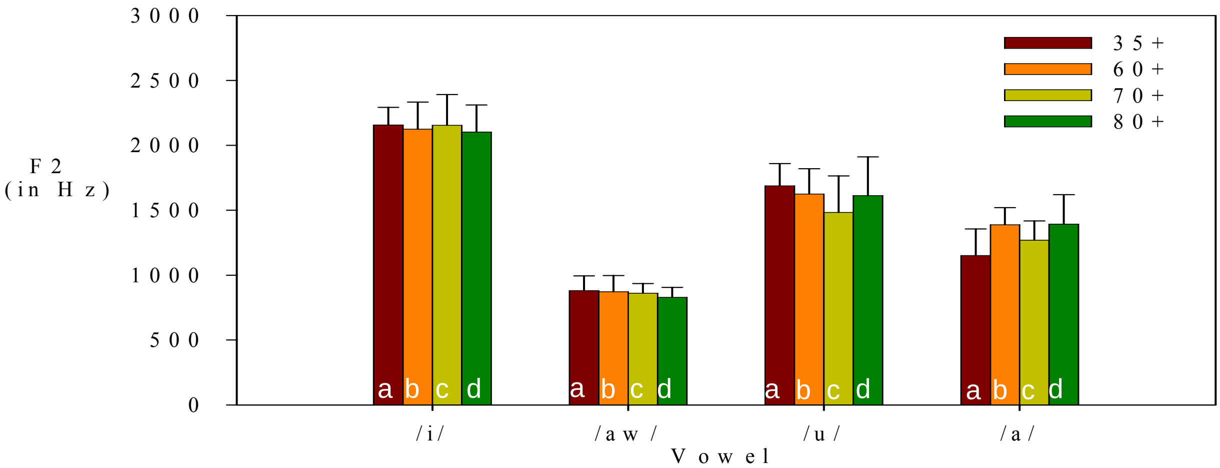


Figure 39.24 - Males F2
Age x Vowel Interaction Effect



Appendix 40. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the acoustic measures (F0, %jitter, %shimmer, SNR, F1, F2, and H1-H2 amplitude difference) for the isolated vowel /a/ sustained at normal pitch and the embedded vowels /i, ɔ, u, a/ in normal pitch and the VOT measures from the sentence. Number of participants: females = 56 and males = 29, n = the number of tokens (2 posture x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture Effect
			F0	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 3.303, **p = 0.027***	F(1,52) = 86.130 , **p < 0.001****	F(3,52) = 4.008**, p = 0.012***
Males	58	F(3,25) = 3.862, **p = 0.021***	F(1,25) = 18.508, **p < 0.001****	F(3,25) = 6.038, **p = 0.003***
Embedded /a/				
Females	112	F(3,52) = 1.183, p = 0.325	F(1,52) = 11.042, **p = 0.002***	F(3,52) = 1.357, p = 0.266
Males	58	F(3,25) = 1.671, p = 0.199	F(1,25) = 11.912, **p = 0.002***	F(3,25) = 1.207, p = 0.328
Embedded /i/				
Females	112	F(3,52) = 1.239, p = 0.305	F(1,52) = 11.041, **p = 0.002***	F(3,52) = 3.052, **p = 0.037***
Males	58	F(3,25) = 5.949, **p = 0.003***	F(1,25) = 6.842, **p = 0.015***	F(3,25) = 0.694, p = 0.564
Embedded /ɔ /				
Females	112	F(3,52) = 3.057, **p = 0.036***	F(1,52) = 7.796, **p = 0.007***	F(3,52) = 1.005, p = 0.398
Males	58	F(3,25) = 4.036, **p = 0.018***	F(1,25) = 13.942, **p < 0.001****	F(3,25) = 1.857, p = 0.163
Embedded /u/				
Females	112	F(3,52) = 0.271, p = 0.846	F(1,52) = 17.681, **p < 0.001****	F(3,52) = 2.096, p = 0.112
Males	58	F(3,25) = 3.411, **p = 0.033***	F(1,25) = 6.224, **p = 0.020***	F(3,25) = 1.677, p = 0.197
			%jitter	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 6.151, **p = 0.001***	F(1,52) = 0.049, p = 0.827	F(3,52) = 0.413, p = 0.745
Males	58	F(3,25) = 0.211, p = 0.888	F(1,25) = 7.644, **p = 0.011***	F(3,25) = 0.494, p = 0.689
Embedded /a/				
Females	112	F(3,52) = 0.723, p = 0.543	F(1,52) = 14.077, **p < 0.001****	F(3,52) = 0.900, p = 0.447
Males	58	F(3,25) = 0.148, p = 0.930	F(1,25) = 0.739, p = 0.398	F(3,25) = 1.779, p = 0.177
Embedded /i/				
Females	112	F(3,52) = 2.768, p = 0.051	F(1,52) = 6.664, **p = 0.013***	F(3,52) = 0.119, p = 0.948
Males	58	F(3,25) = 0.523, p = 0.671	F(1,25) = 14.814, **p < 0.001****	F(3,25) = 1.944, p = 0.148
Embedded /ɔ /				
Females	112	F(3,52) = 1.106, p = 0.355	F(1,52) = 5.752, **p = 0.020***	F(3,52) = 1.138, p = 0.342
Males	58	F(3,25) = 1.084, p = 0.374	F(1,25) = 6.582, **p = 0.017***	F(3,25) = 0.327, p = 0.806
Embedded /u/				
Females	112	F(3,52) = 0.687, p = 0.564	F(1,52) = 9.310, **p = 0.004***	F(3,52) = 1.010, p = 0.396
Males	58	F(3,25) = 1.366, p = 0.276	F(1,25) = 4.923, **p = 0.036***	F(3,25) = 0.739, p = 0.539

	n	Age effect	Posture Effect	Age x Posture Effect
			%shimmer	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 4.667, **p = 0.006***	F(1,52) = 0.001, p = 0.976	F(3,52) = 0.684, p = 0.566
Males	58	F(3,25) = 0.220, p = 0.881	F(1,25) = 3.932, p = 0.058	F(3,25) = 1.989, p = 0.141
Embedded /a/				
Females	112	F(3,52) = 1.152, p = 0.337	F(1,52) = 4.597, **p = 0.037***	F(3,52) = 0.493, p = 0.689
Males	58	F(3,25) = 0.698, p = 0.562	F(1,25) = 0.005, p = 0.947	F(3,25) = 3.550, p = **0.029***
Embedded /i/				
Females	112	F(3,52) = 0.899, p = 0.448	F(1,52) = 14.582, **p < 0.001****	F(3,52) = 0.630, p = 0.599
Males	58	F(3,25) = 1.628, p = 0.208	F(1,25) = 6.948, **p = 0.014***	F(3,25) = 1.429, p = 0.258
Embedded /ɔ /				
Females	112	F(3,52) = 1.053, p = 0.377	F(1,52) = 2.325, p = 0.133	F(3,52) = 0.825, p = 0.486
Males	58	F(3,25) = 2.169, p = 0.117	F(1,25) = 4.571, **p = 0.042***	F(3,25) = 0.569, p = 0.641
Embedded /u/				
Females	112	F(3,52) = 0.288, p = 0.834	F(1,52) = 13.023, **p < 0.001****	F(3,52) = 0.166, p = 0.919
Males	58	F(3,25) = 2.487, p = 0.084	F(1,25) = 4.036, p = 0.055	F(3,25) = 0.786, p = 0.513
			SNR	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 2.874, **p = 0.045***	F(1,52) = 0.463, p = 0.499	F(3,52) = 1.362, p = 0.265
Males	58	F(3,25) = 0.212, p = 0.887	F(1,25) = 1.374, p = 0.252	F(3,25) = 2.366, p = 0.095
Embedded /a/				
Females	112	F(3,52) = 1.303, p = 0.283	F(1,52) = 1.910 , p = 0.173	F(3,52) = 2.052, p = 0.118
Males	58	F(3,25) = 0.170, p = 0.915	F(1,25) = 0.107, p = 0.746	F(3,25) = 1.967, p = 0.145
Embedded /i/				
Females	112	F(3,52) = 1.812, p = 0.157	F(1,52) = 5.493, **p = 0.023***	F(3,52) = 0.220, p = 0.882
Males	58	F(3,25) = 1.748, p = 0.183	F(1,25) = 10.565, **p = 0.003***	F(3,25) = 2.574, p = 0.077
Embedded /ɔ /				
Females	112	F(3,52) = 1.362, p = 0.265	F(1,52) = 11.426, **p = 0.001***	F(3,52) = 0.675, p = 0.572
Males	58	F(3,25) = 2.227, p = 0.110	F(1,25) = 9.097, **p = 0.006***	F(3,25) = 0.554, p = 0.650
Embedded /u/				
Females	112	F(3,52) = 0.004, p = 1.000	F(1,52) = 29.637, **p < 0.001****	F(3,52) = 0.592, p = 0.623
Males	58	F(3,25) = 1.939, p = 0.149	F(1,25) = 24.744, **p < 0.001****	F(3,25) = 0.850, p = 0.479

	n	Age effect	Posture Effect	Age x Posture Effect
			F1	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 0.532, p = 0.663	F(1,52) = 7.741, p = **0.008***	F(3,52) = 1.475, p = 0.232
Males	58	F(3,25) = 1.154, p = 0.347	F(1,25) = 0.795, p = 0.381	F(3,25) = 0.765, p = 0.525
Embedded /a/				
Females	112	F(3,52) = 0.925, p = 0.435	F(1,52) = 13.005, p < **0.001****	F(3,52) = 0.579, p = 0.632
Males	58	F(3,25) = 2.353, p = 0.096	F(1,25) = 8.953, p = **0.006***	F(3,25) = 1.110, p = 0.364
Embedded /i/				
Females	112	F(3,52) = 1.250, p = 0.301	F(1,52) = 2.867, p = 0.096	F(3,52) = 0.108, p = 0.955
Males	58	F(3,25) = 1.169, p = 0.341	F(1,25) = 0.467, p = 0.501	F(3,25) = 3.014, **p = 0.049**
Embedded /ɔ /				
Females	112	F(3,52) = 1.240, p = 0.305	F(1,52) = 31.781, **p < 0.001****	F(3,52) = 0.932, p = 0.432
Males	58	F(3,25) = 0.840, p = 0.485	F(1,25) = 14.712, **p < 0.001****	F(3,25) = 1.839, p = 0.166
Embedded /u/				
Females	112	F(3,52) = 1.857, p = 0.148	F(1,52) = 18.332, **p < 0.001****	F(3,52) = 0.824, p = 0.487
Males	58	F(3,25) = 0.150, p = 0.929	F(1,25) = 4.499, **p = 0.044***	F(3,25) = 1.320, p = 0.290
			F2	
Isolated /a/ in Normal Pitch				
Females	112	F(3,52) = 3.797, p = **0.015***	F(1,52) = 6.942, p **= 0.011***	F(3,52) = 0.503, p = 0.862
Males	58	F(3,25) = 1.622, p = 0.209	F(1,25) = 12.389, p = **0.002***	F(3,25) = 0.248, p = 0.862
Embedded /a/				
Females	112	F(3,52) = 3.238, p = **0.029***	F(1,52) = 36.522, p < **0.001****	F(3,52) = 0.125, p = 0.945
Males	58	F(3,25) = 3.031, p = **0.048***	F(1,25) = 0.001, p = 0.974	F(3,25) = 1.078, p = 0.376
Embedded /i/				
Females	112	F(3,52) = 0.486, p = 0.694	F(1,52) = 20.010, **p < 0.001****	F(3,52) = 0.451, p = 0.718
Males	58	F(3,25) = 0.129, p = 0.942	F(1,25) = 0.092, p = 0.764	F(3,25) = 0.467, p = 0.708
Embedded /ɔ /				
Females	112	F(3,52) = 0.772, p = 0.515	F(1,52) = 4.547, **p = 0.038***	F(3,52) = 0.314, p = 0.815
Males	58	F(3,25) = 0.552, p = 0.651	F(1,25) = 3.711, p = 0.066	F(3,25) = 0.036, p = 0.991
Embedded /u/				
Females	112	F(3,52) = 0.543, p = 0.655	F(1,52) = 46.224, **p < 0.001****	F(3,52) = 0.741, p = 0.533
Males	58	F(3,25) = 1.070, p = 0.380	F(1,25) = 7.232, **p = 0.013***	F(3,25) = 0.593, p = 0.626

	n	Age effect	Posture Effect	Age x Posture Effect
			H1-H2 Amplitude Difference	
Isolated /a/ in Normal Pitch				
Females	112	$F(3,52) = 1.868$, $p = 0.146$	$F(1,52) = 17.075$, $p <$ **0.001****	$F(3,52) = 2.394$, $p = 0.079$
Males	58	$F(3,25) = 1.958$, $p = 0.146$	$F(1,25) = 3.861$, $p = 0.061$	$F(3,25) = 0.513$, $p = 0.677$
			VOT	
Embedded /ka/				
Females	112	$F(3,52) = 3.198$, **p = 0.031***	$F(1,52) = 6.513$, **p = 0.014***	$F(3,52) = 0.718$, $p = 0.546$
Males	58	$F(3,25) = 7.992$, **p < 0.001****	$F(1,25) = 5.629$, **p = 0.026***	$F(3,25) = 2.139$, $p = 0.121$
Embedded /tu/				
Females	112	$F(3,52) =1.703$, $p = 0.178$	$F(1,52) =1.890$, $p = 0.175$	$F(3,52) = 0.223$, $p = 0.880$
Males	58	$F(3,25) =4.609$, **p = 0.011***	$F(1,25) = 5.041$, **p = 0.034***	$F(3,25) = 2.361$, $p = 0.095$

*Significant at 0.05 level **Significant at 0.005 level

Appendix 41. Bar charts of the two-way (2 jaw postures X 4 age groups) mixed model ANOVA results for the vowel /a/ sustained at normal pitch and the embedded vowel /a/ in the word "cars" from the sentence "We saw two cars" for females (n = 56) and males (n = 29).

Notes:
(1) Groups significantly different are marked with different letters.
(2) "*" Indicates a significant difference between the paired groups.
(3) "n" indicates the number of participants in each age group.

Figure 41.1 - Females F0
Isolated /a/
Age x Posture Interaction Effect

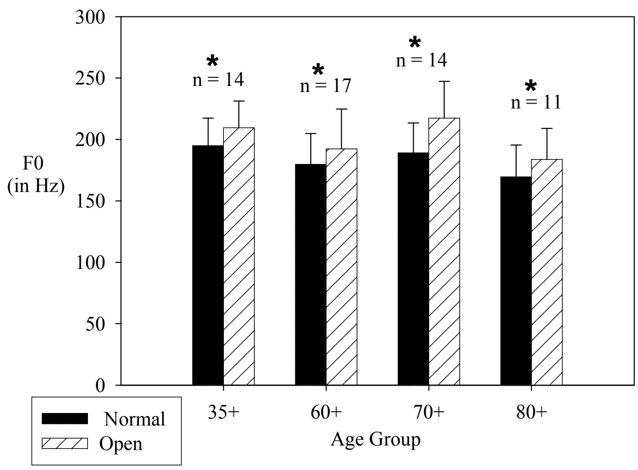


Figure 41.2 - Males F0
Isolated /a/
Age x Posture Interaction Effect

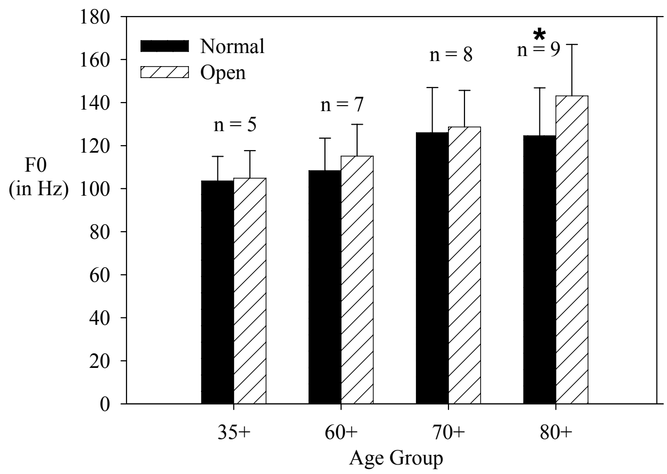


Figure 41.3 - Females and Males F0
Embedded /a/
Posture Effect

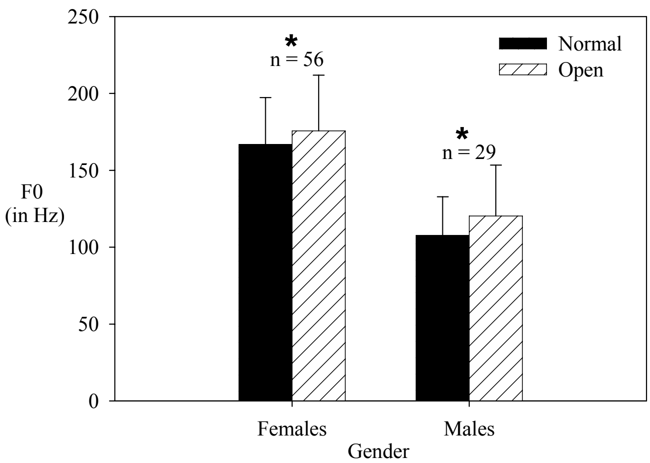


Figure 41.4 - Females %jitter
Isolated /a/
Age effect

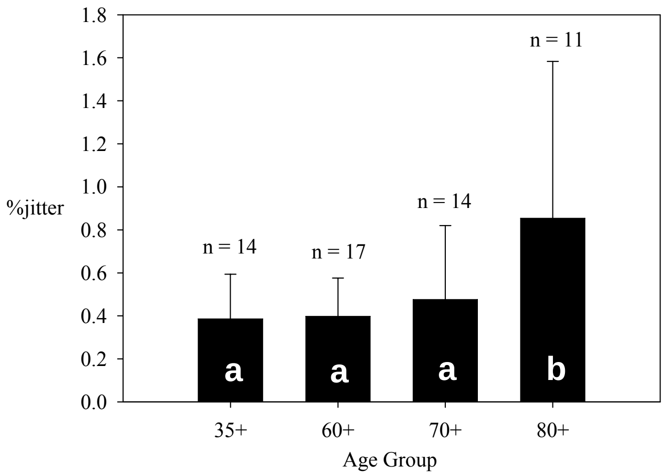


Figure 41.5 - Males %jitter
Isolated /a/
Posture Effect

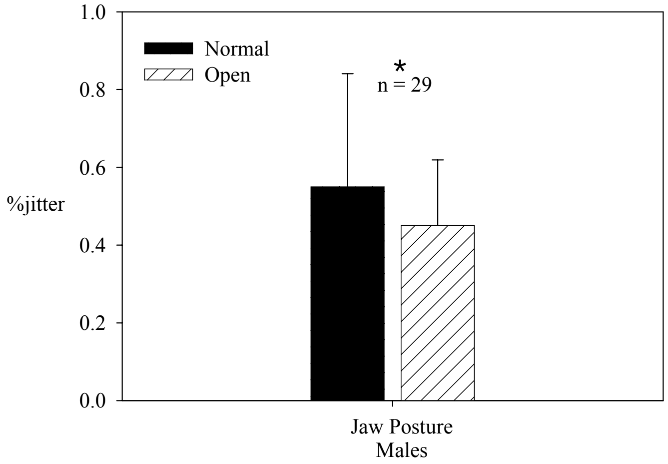


Figure 41.6 - Females %jitter
Embedded /a/
Posture Effect

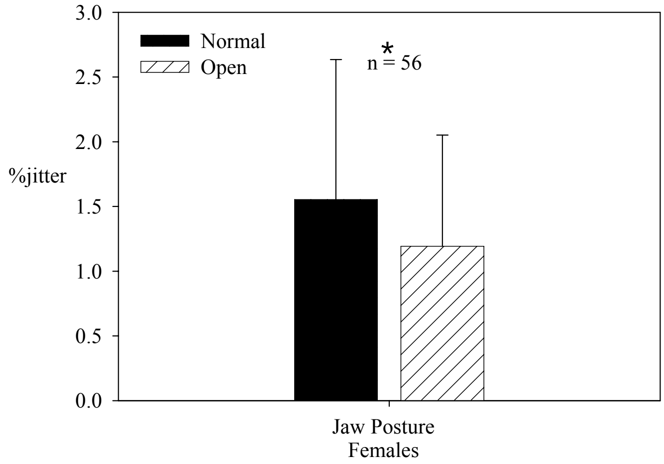


Figure 41.7 - Females %shimmer
Isolated /a/
Age effect

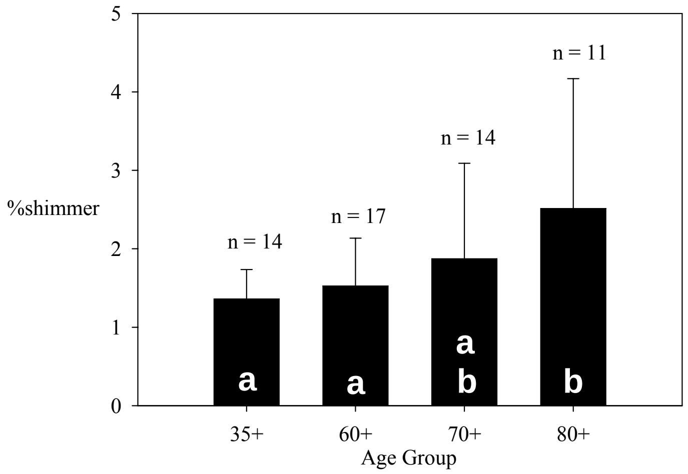


Figure 41.8 - Females %shimmer
Embedded /a/
Posture Effect

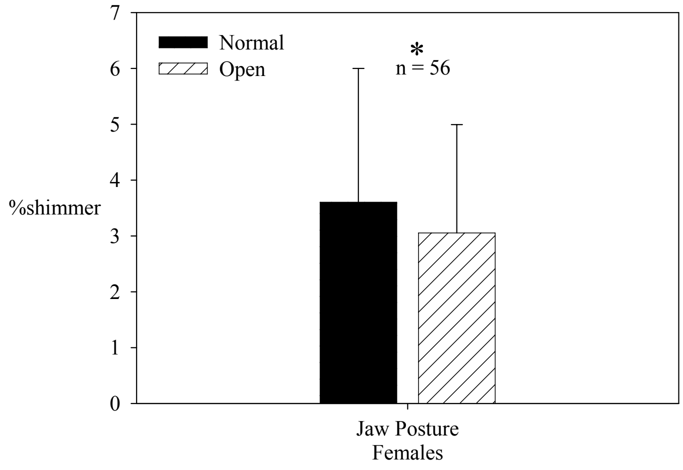


**Figure 41.9 - Males %shimmer
Embedded /a/
Age x Posture Interaction Effect**

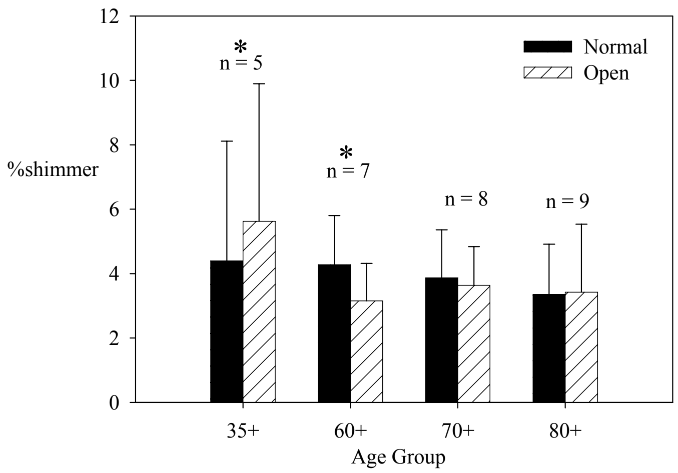


**Figure 41.10 - Females SNR
Isolated /a/
Age effect**

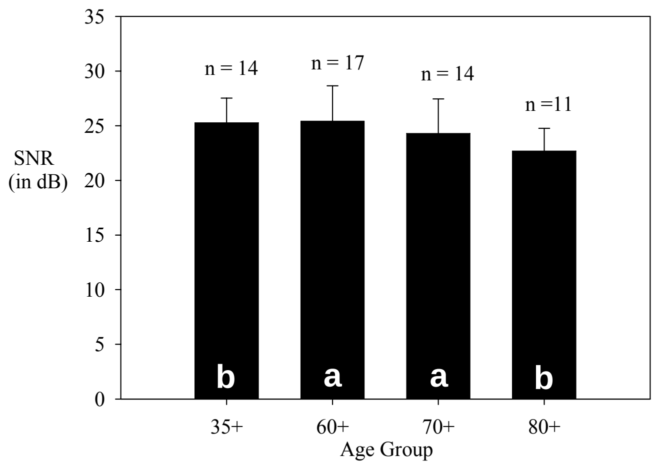


**Figure 41.11 - Females F1
Isolated /a/
Posture Effect**

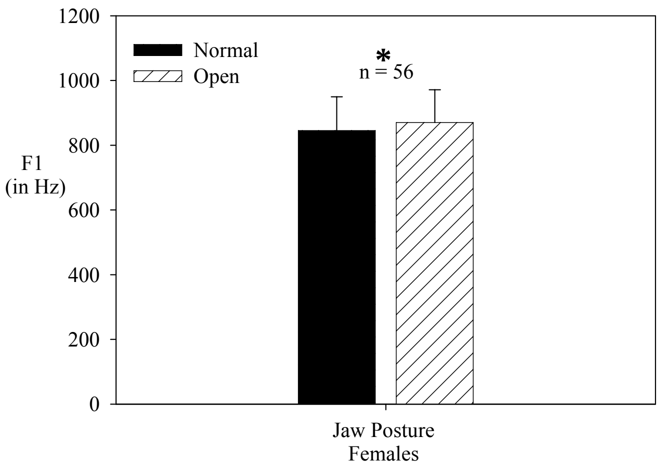


**Figure 41.12 - Females and Males F1
Embedded /a/
Posture Effect**

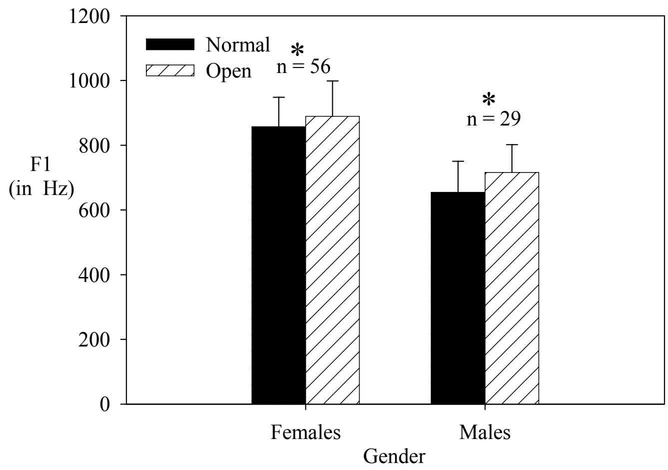


Figure 41.13 - Females F2
Isolated /a/
Age effect

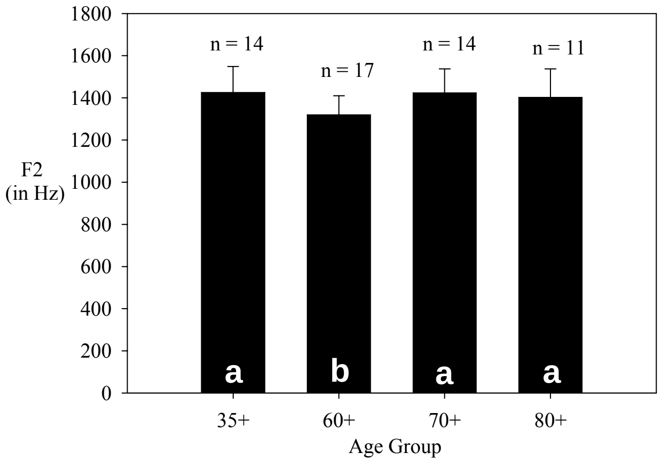


Figure 41.14 - Females and Males F2
Isolated /a/
Posture Effect

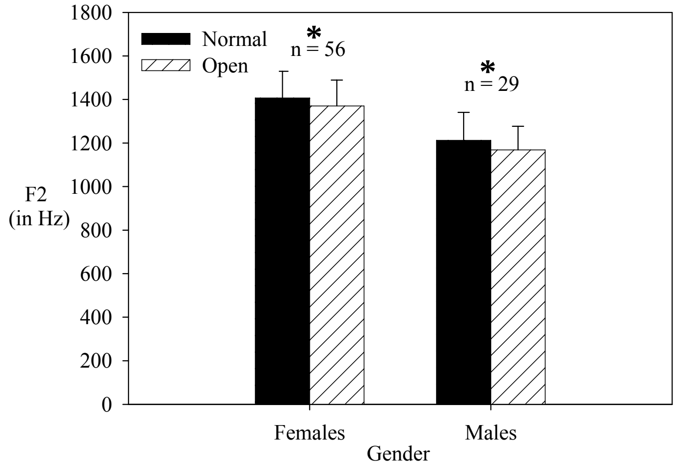


Figure 41.15 - Females F2
Embedded /a/
Posture Effect

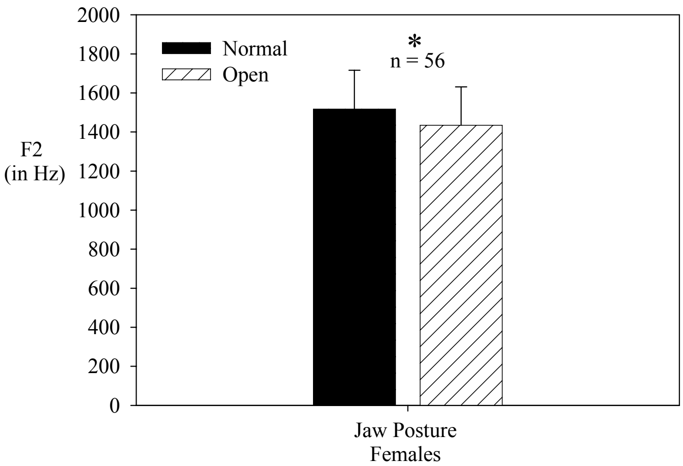


Figure 41.16 - Females F2
Embedded /a/
Age effect

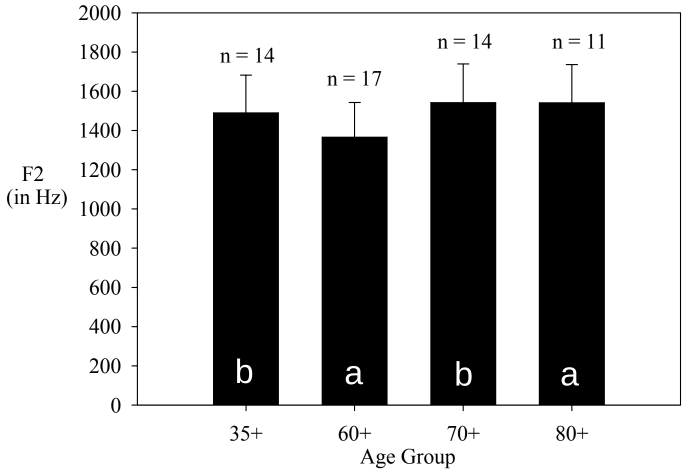


Figure 41.17 - Males F2
Embedded /a/
Age effect

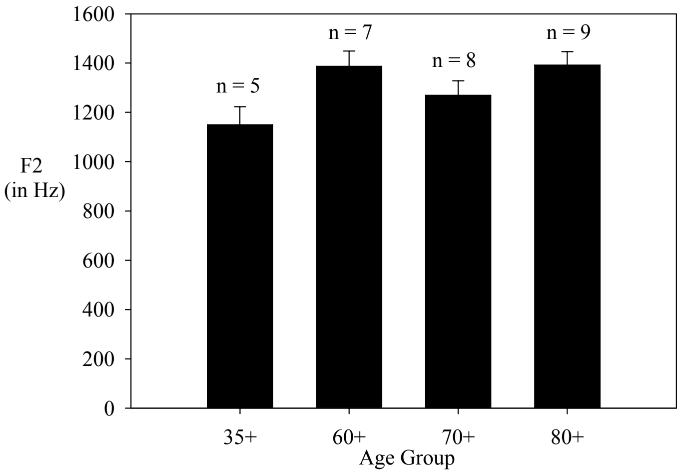


Figure 41.18a - Females and Males VOT
Measured from the word “cars”
Posture Effect

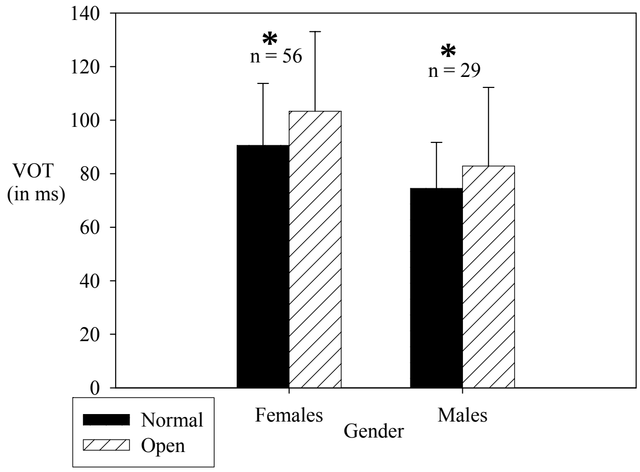


Figure 41.18b - Males VOT
Measures from the word “two”
Posture Effect

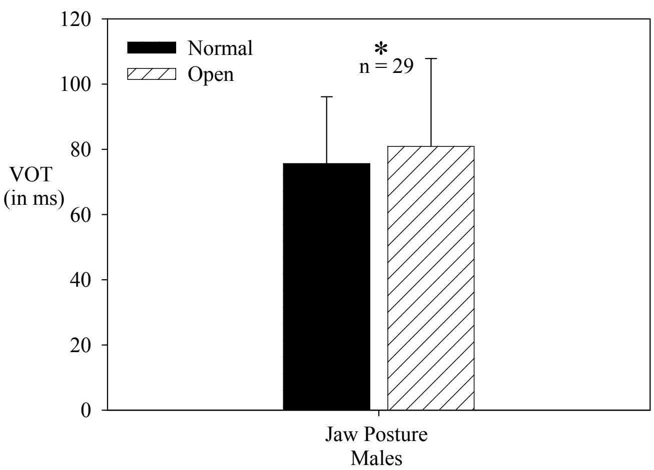


Figure 41.19 - Females VOT
Measured from the word “cars”
Age effect

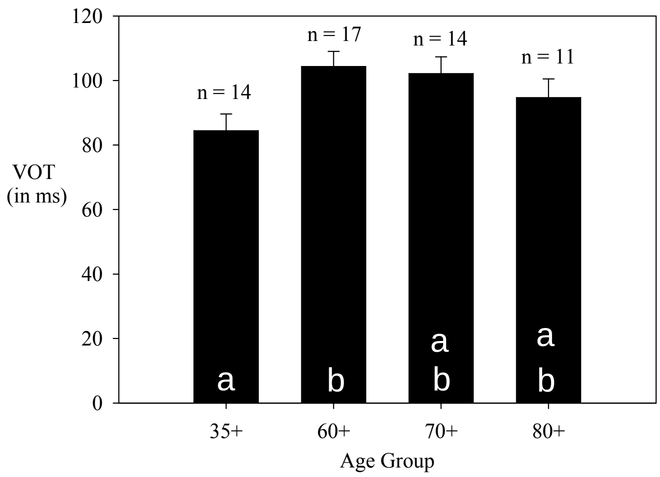


Figure 41.20a - Males VOT Measured from the word "cars" Age effect

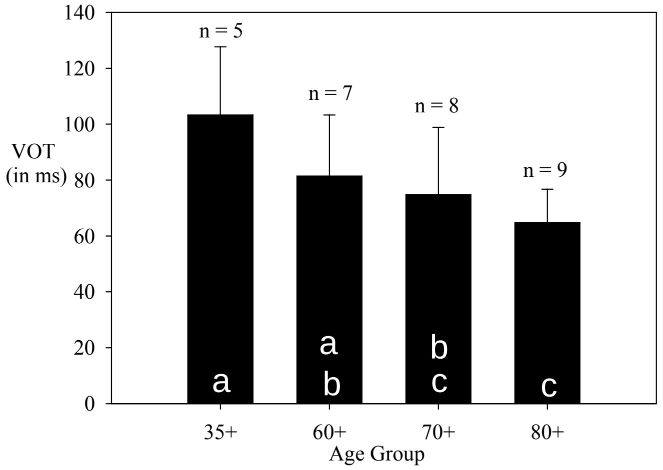


Figure 41.20b - Males VOT Measured from the word "two" Age effect

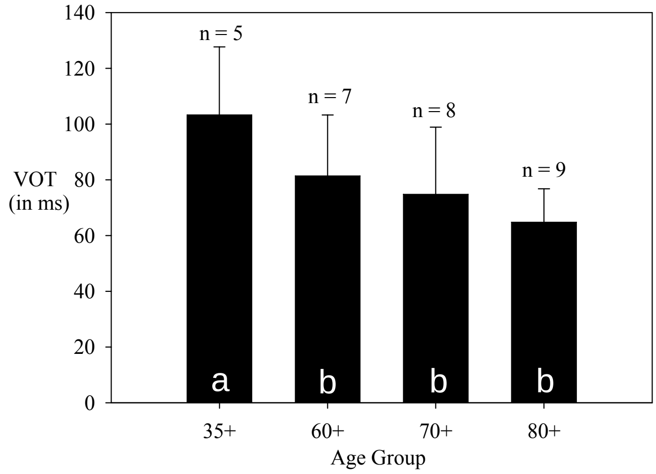


Figure 41.21 - Females H1-H2 Posture Effect

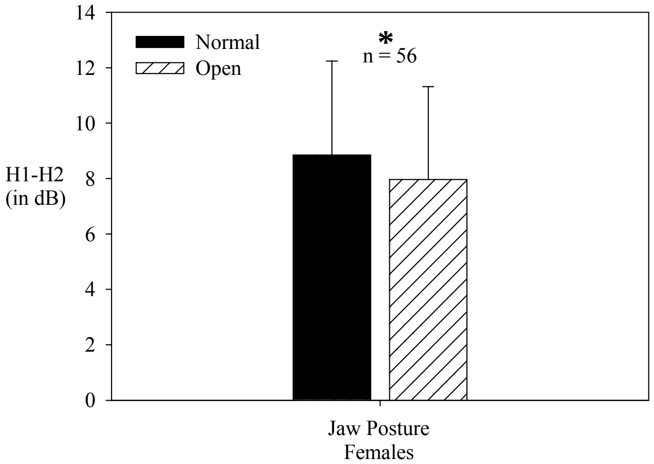


Figure 41.22 - Females and Males SPL Posture Effect

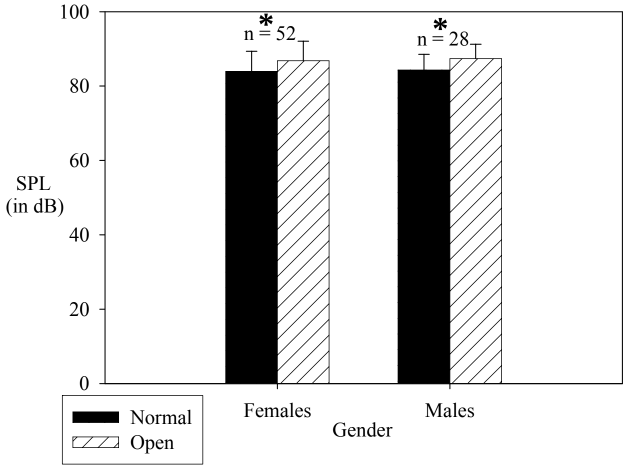


Figure 41.23 - Females and Males MFR Isolated /a/ Posture Effect

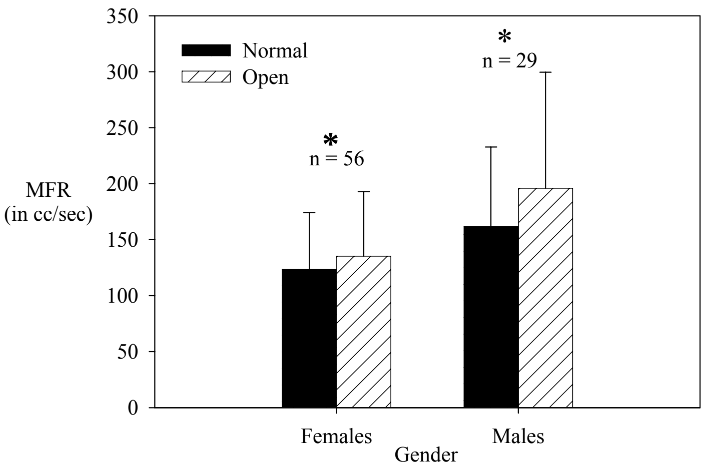


Figure 41.24 – Females Air Pressure Posture Effect

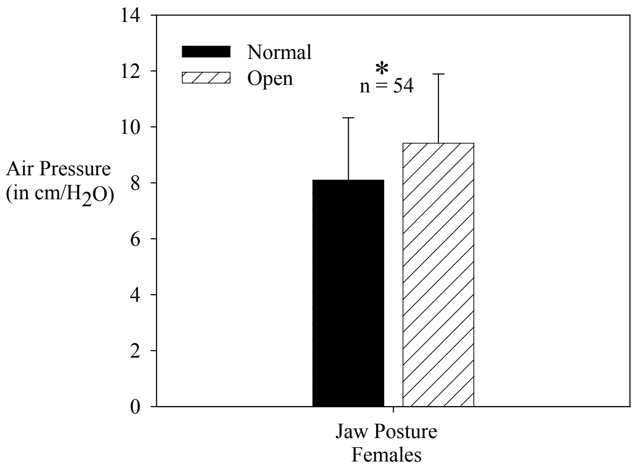


Figure 41.25 - Females and Male Airflow rate Posture Effect

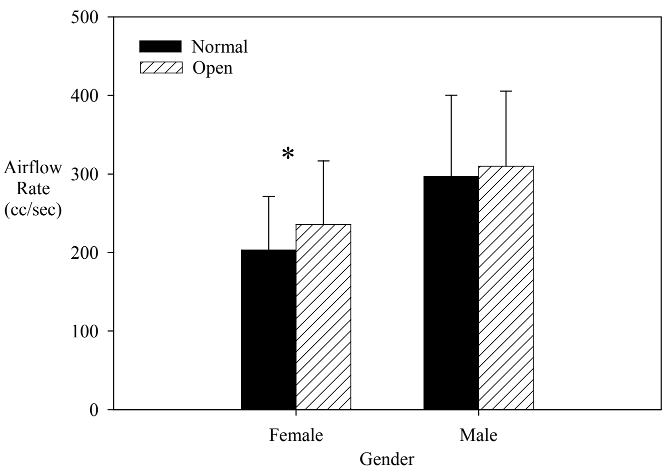
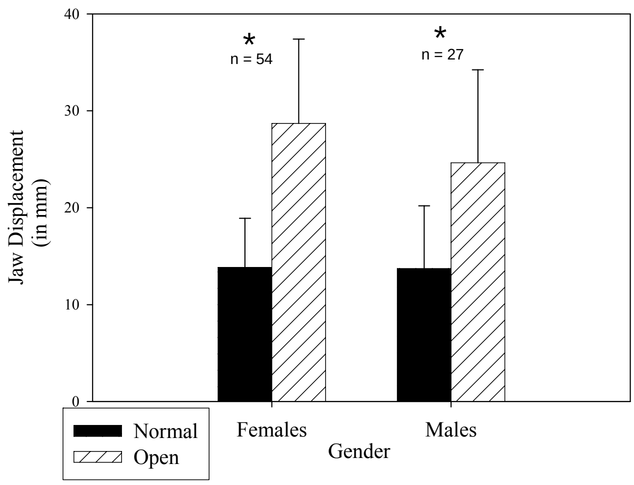


Figure 41.26 - Females and Males Jaw Displacement Posture Effect



Appendix 42. Results from the three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVAs performed on the EGG measures for the vowel /a/ sustained in a one-syllable task (normal, high, and low pitch and /m/ and /h/-initiated). The age group factor has four levels: 35+, 60+, 70+, and 80+. The jaw posture factor has two levels: normal and open jaw. The task factor has five levels: normal pitch, high pitch, low pitch, and /m/ and /h/ initiated. Number of participants: females = 38 and males = 27, n = the number of tokens (2 posture 5 tasks x number of participants) submitted for analysis.

Effect	Females (n =380)	Males (n = 266)[§]
F0		
Age	F(3, 340) = 6.838, **p < 0.001****	F(3, 226) = 22.288, **p < 0.001***
Posture	F(1, 340) = 6.955, **p = 0.009***	F(1, 226) = 7.535, **p = 0.007***
Task	F(4, 340) = 32.582, **p < 0.001****	F(4, 226) = 54.848, **p < 0.001****
Age x Posture	F(3, 340) = 0.679, p = 0.566	F(3, 226) = 0.455, p = 0.714
Age x Task	F(12, 340) = 0.632, p = 0.815	F(12, 226) = 0.233, p = 0.997
Posture x Task	F(4, 340) = 0.236, p = 0.918	F(4,226) = 0.377, p = 0.825
Age x Posture x Task	F(12, 340) = 0.652, p = 0.797	F(12,226) = 0.135, p = 1.000
SQ		
Age	F(3,340) = 3.951, **p = 0.009***	F(3, 226) = 6.947, **p < 0.001****
Posture	F(1, 340) = 0.923, p = 0.337	F(1, 226) = 1.618, p = 0.205
Task	F(4, 340) = 0.356, p = 0.840	F(4, 226) = 1.673, p = 0.157
Age x Posture	F(3, 340) = 0.218, p = 0.884	F(3, 226) = 0.572, p = 0.634
Age x Task	F(12, 340) = 0.363, p = 0.975	F(12, 226) = 0.478, p = 0.926
Posture x Task	F(4, 340) = 0.465, p = 0.762	F(4, 226) = 0.253, p = 0.908
Age x Posture x Task	F(12, 340) = 0.140, p = 1.000	F(12, 226) = 0.254, p = 0.995
OQ		
Age	F(3, 340) = 4.971, **p = 0.002***	F(3, 226) = 7.988, **p < 0.001****
Posture	F(1, 340) = 1.127, p = 0.289	F(1, 226) = 2.044, p = 0.154
Task	F(4, 340) = 0.350, p = 0.844	F(4, 226) = 2.357, p = 0.055
Age x Posture	F(3, 340) = 0.362, p = 0.780	F(3, 226) = 0.747, p = 0.525
Age x Task	F(12, 340) = 0.265, p = 0.994	F(12, 226) = 0.410, p = 0.959
Posture x Task	F(4, 340) = 0.235, p = 0.919	F(4,226) = 0.211, p = 0.932
Age x Posture x Task	F(12, 340) = 0.250, p =0.995	F(12,226) = 0.309, p = 0.987

*Significant at 0.05 level **Significant at 0.005 level [§]Missing Data

Appendix 43. EGG bar charts of the three-way (2 jaw postures X 4 age groups X 5 tasks) ANOVA results for the vowel /a/ sustained in a one-syllable task (normal, high and low pitch and /m/ and /h/-initiated in normal pitch) and the two-way (2 jaw postures X 4 age groups) mixed model ANOVA results for the isolated vowel /a/ sustained at normal pitch, females = 38 and males = 27.

Notes: (1) Groups significantly different are marked with different letters.
(2) "*" indicates a significant difference between the paired groups.

Figure 43.1 - Females EGG F0
Age effect

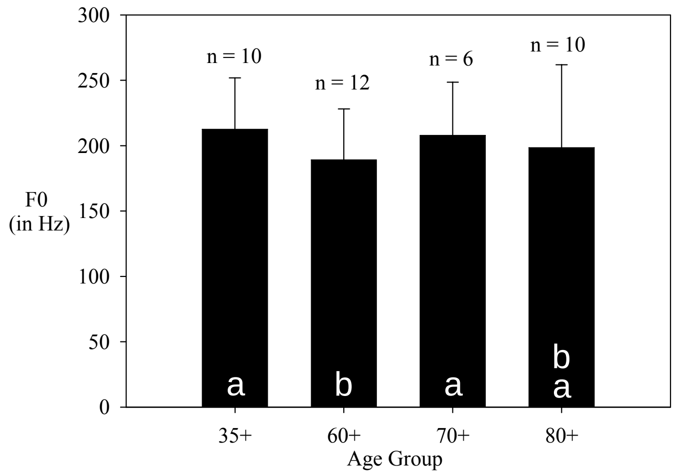


Figure 43.2 - Males EGG F0
Age effect

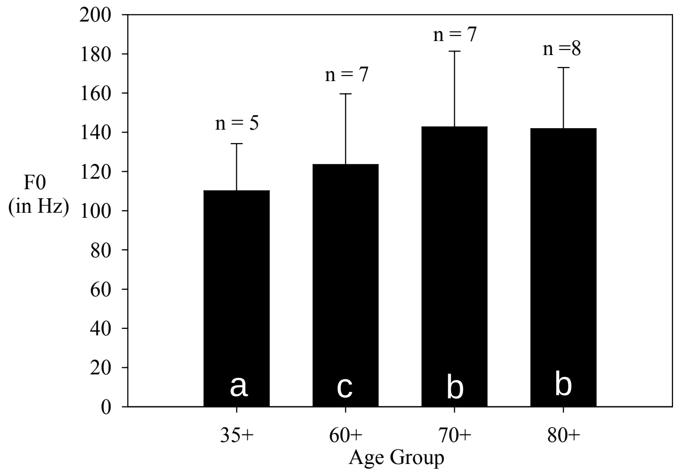


Figure 43.3 - Males EGG F0
Isolated Vowel /a/
Age effect

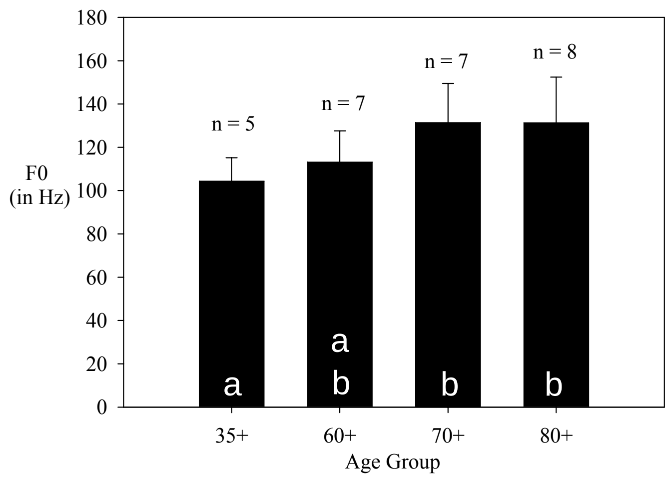


Figure 43.4 - Females and Males EGG F0
Isolated Vowel /a/
Posture Effect

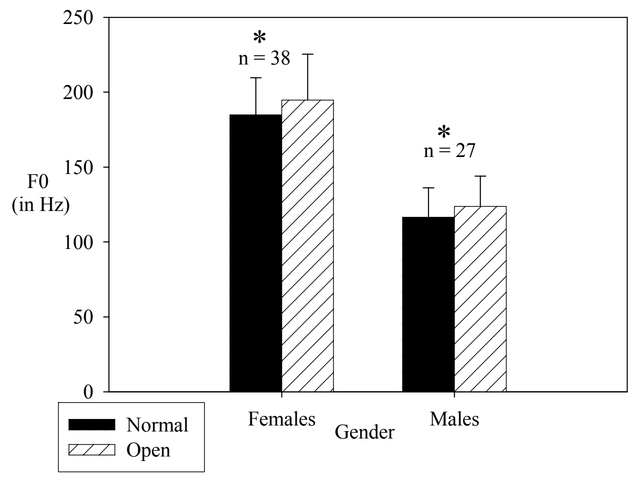


Figure 43.5 - Females and Males EGG F0
Posture Effect

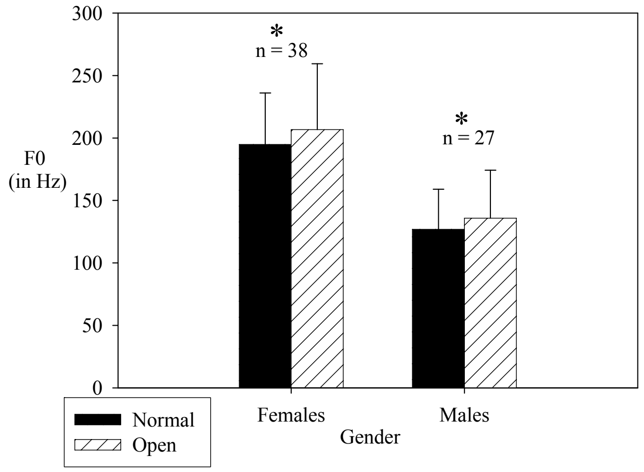


Figure 43.6 - Females EGG F0
Task Effect

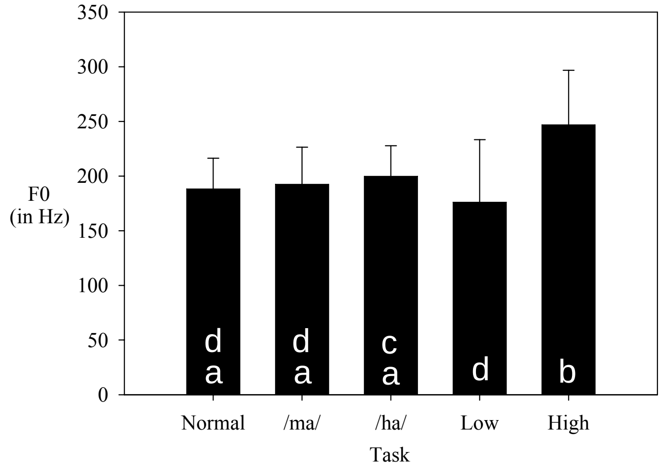


Figure 43.7 - Males EGG F0
Task Effect

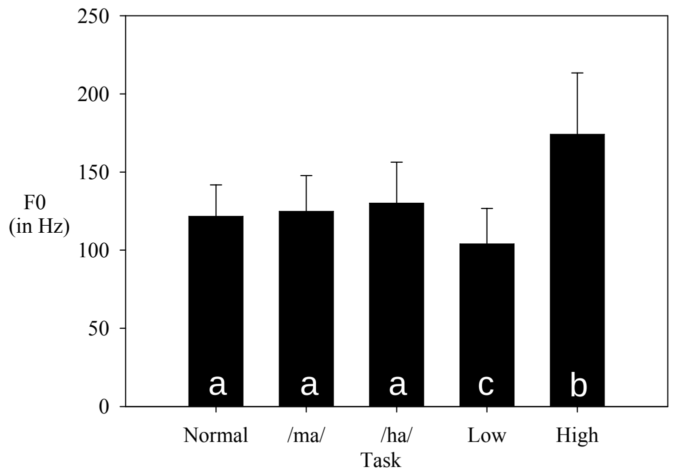


Figure 43.8 - Females SQ
Age effect

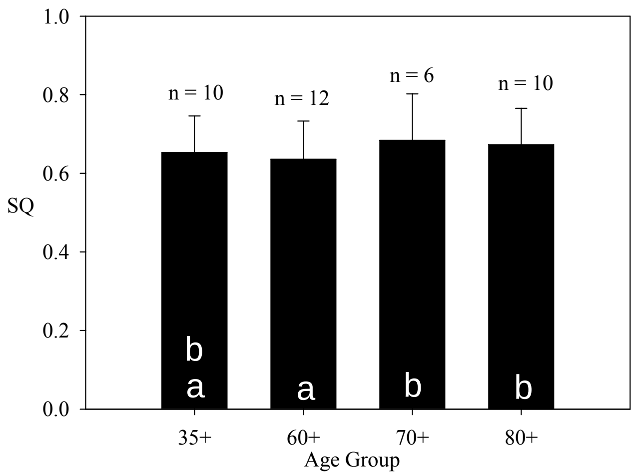


Figure 43.9 - Males SQ
Age effect

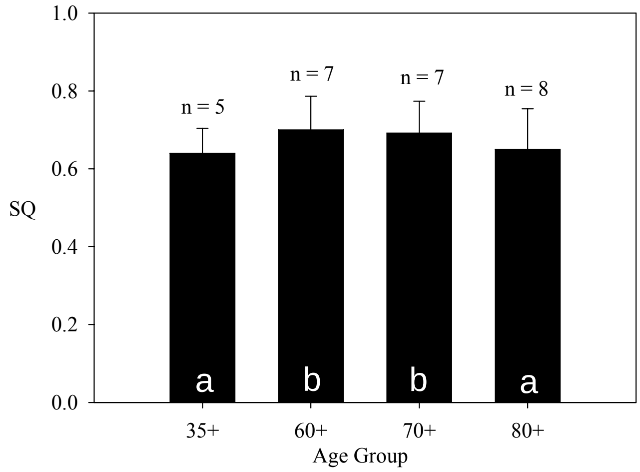


Figure 43.10 - Females OQ
Age effect

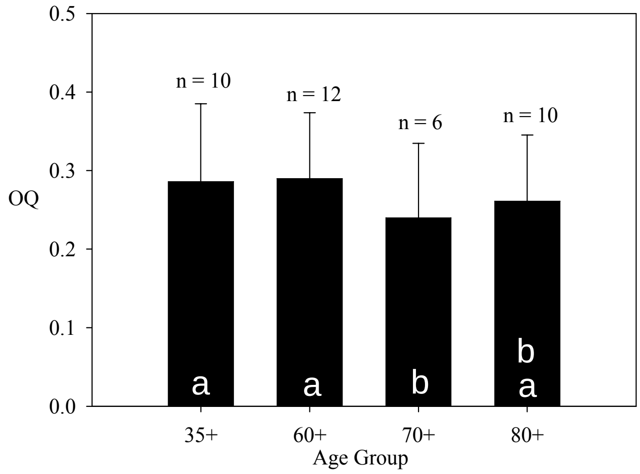


Figure 43.11 - Males OQ
Age effect

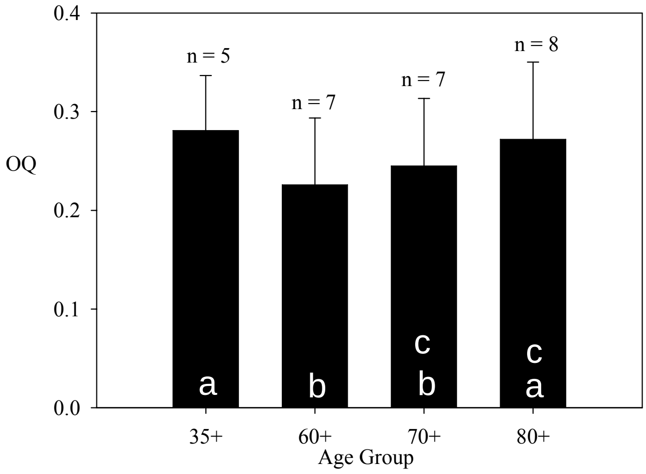
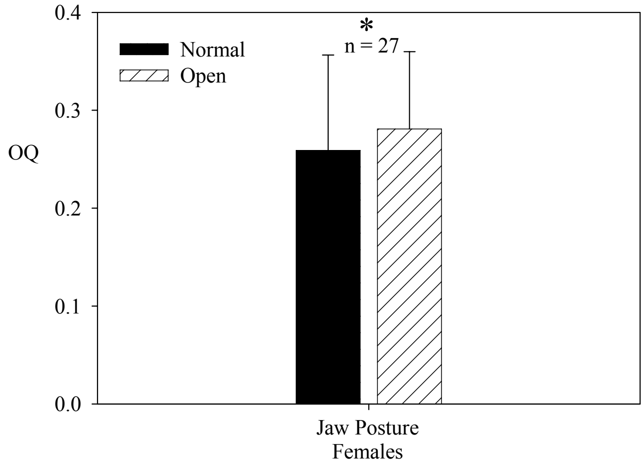


Figure 43.12 - Females OQ
Isolated Vowel /a/
Posture Effect



Appendix 44. Results from three-way (2 jaw postures X 4 age groups X 4 vowels) ANOVAs performed on EGG measures (F0, SQ, and OQ) for the vowels /i, ɔ, u, a/ embedded in the sentence "We saw two cars." produced in two jaw postures (normal and open). Number of participants: females = 33 and males = 16, n = the number of tokens (2 posture 4 vowels x nbr of participants) submitted for analysis.

Effect	Females (n = 264)	Males (n = 128)
F0		
Age	F(3,232) = 8.288, **p < 0.001***	F(3,96) = 45.468, **p < 0.001****
Posture	F(1,232) = 3.590, p = 0.059	F(1,96) = 8.0.16, **p = 0.006***
Vowel	F(3,232) = 38.432, **p < 0.001****	F(3,96) = 8.309, **p < 0.001****
Age x Posture	F(3,232) = 0.281, p = 0.839	F(3,96) = 6.209, **p < 0.001****
Age x Vowel	F(9,232) = 1.124, p = 0.346	F(9,96) = 0.279, p = 0.979
Posture x Vowel	F(3,232) = 0.436, p = 0.727	F(3,96) = 0.249, p = 0.862
Age x Posture x Vowel	F(9,232) = 0.368, p = 0.950	F(9,96) = 0.355, p = 0.953
SQ		
Age	F(3,232) = 4.228, **p = 0.006***	F(3,96) = 5.343, **p = 0.002***
Posture	F(1,232) = 0.007, p = 0.932	F(1,96) = 0.097, p = 0.756
Vowel	F(3,232) = 0.556, p = 0.644	F(3,96) = 0.494, p = 0.687
Age x Posture	F(3,232) = 0.084, p = 0.969	F(3,96) = 1.013, p = 0.391
Age x Vowel	F(9,232) = 0.176, p = 0.996	F(9,96) = 0.692, p = 0.715
Posture x Vowel	F(3,232) = 0.083, p = 0.969	F(3,96) = 0.118, p = 0.950
Age x Posture x Vowel	F(9,232) = 0.058, p = 1.000	F(9,96) = 0.281, p = 0.978
OQ		
Age	F(3, 232) = 4.823, **p = 0.003***	F(3, 96) = 4.459, **p = 0.006***
Posture	F(1, 232) = 0.022, p = 0.882	F(1, 96) = 0.077, p = 0.783
Vowel	F(3, 232) = 1.084, p = 0.356	F(3, 96) = 0.427, p = 0.734
Age x Posture	F(3, 232) = 0.117, p = 0.950	F(3, 96) = 1.002, p = 0.395
Age x Vowel	F(9, 232) = 0.548, p = 0.838	F(9, 96) = 0.875, p = 0.550
Posture x Vowel	F(3, 232) = 0.341, p = 0.796	F(3, 96) = 0.082, p = 0.970
Age x Posture x Vowel	F(9, 232) = 0.169, p = 0.997	F(9, 96) = 0.303, p = 0.972

*Significant at 0.05 level **Significant at 0.005 level

Appendix 45. EGG bar charts of the three-way (2 jaw postures X 4 age groups X 4 vowels) ANOVA results for the embedded vowels /i, ɔ, u, a/ in normal pitch, females = 33 and males = 16

Notes:
(1) The vowel /ɔ/ is written as "aw" in the following graphs.
(2) Groups significantly different are marked with different letters.
(3) "*" indicates a significant difference between the paired groups.

Figure 45.1 - Females EGG F0
Embedded Vowels
Age effect

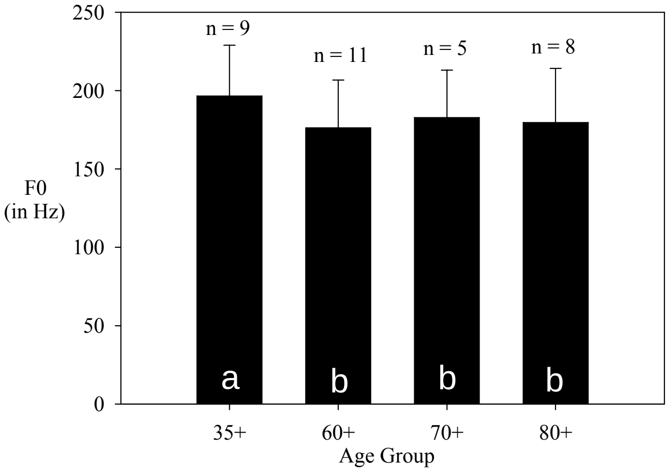


Figure 45.2 - Females EGG F0
Embedded Vowels
Vowel Effect

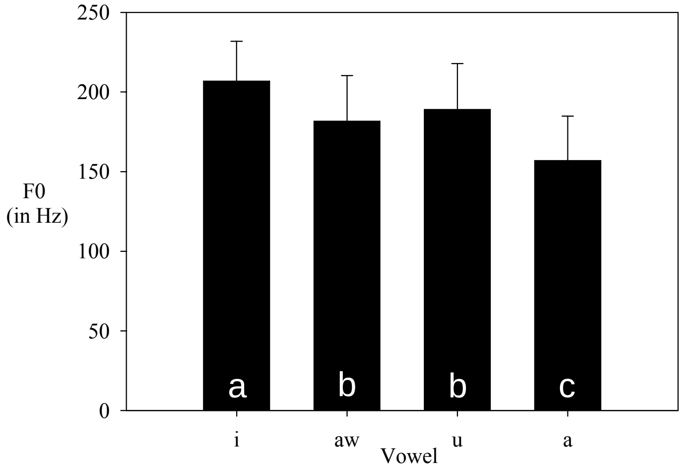


Figure 45.3 - Males EGG F0
Embedded Vowels
Vowel Effect

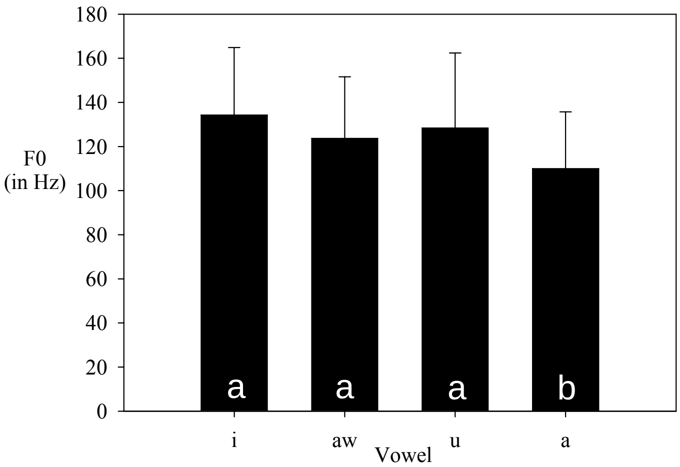


Figure 45.4 - Males EGG F0
Embedded Vowels
Age x Posture Interaction Effect

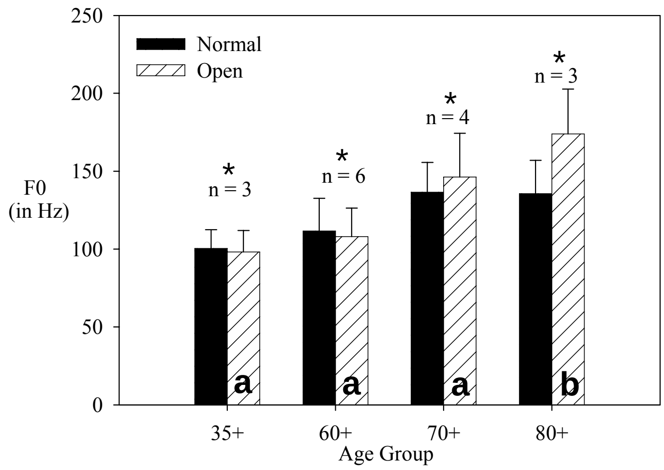


Figure 45.5 - Females EGG F0
Embedded vowel /a/
Posture Effect

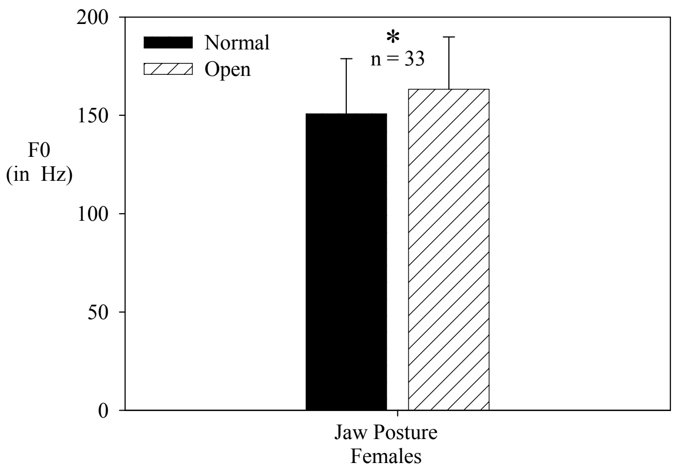


Figure 45.6 - Males EGG F0
Embedded Vowel /a/
Age x Posture Effect

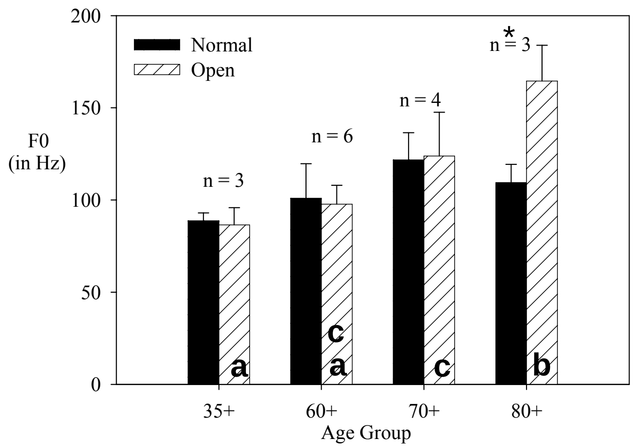


Figure 45.7 - Females SQ
Embedded Vowels
Age effect

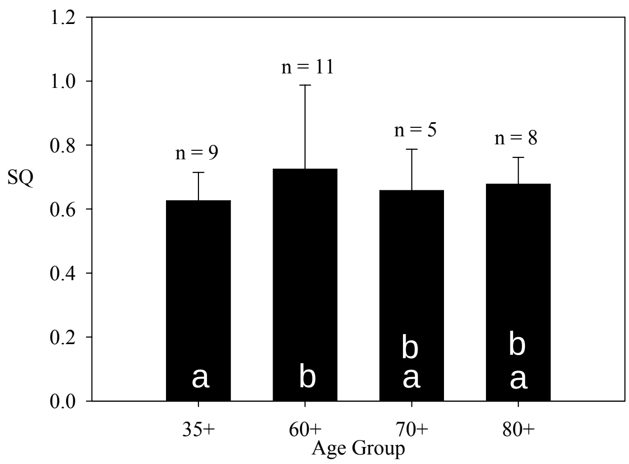


Figure 45.8 - Males SQ
Embedded Vowels
Age effect

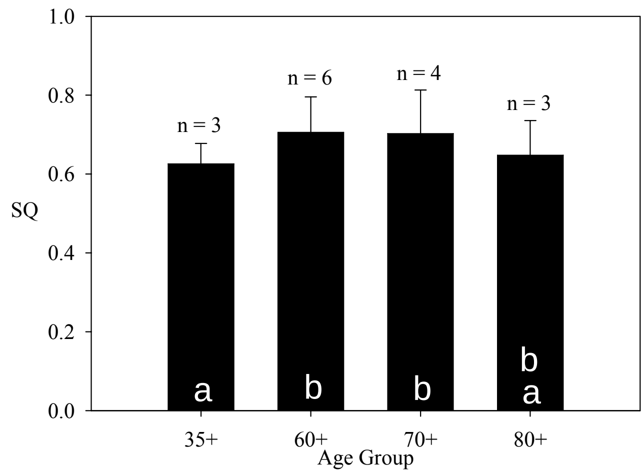


Figure 45.9 - Females OQ
Embedded Vowels
Age effect

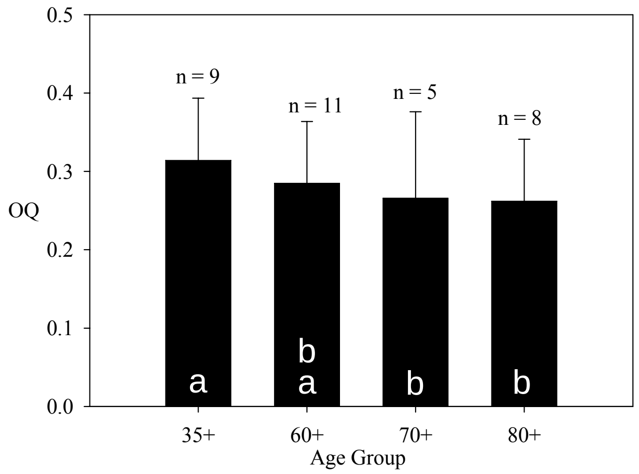
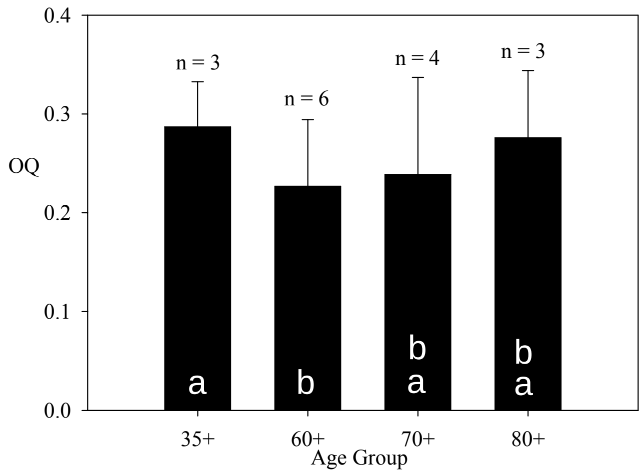


Figure 45.10 - Males OQ
Embedded Vowels
Age effect



Appendix 46. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the EGG measures for the vowel /a/ sustained in a one-syllable task (normal, high, and low pitch and /m/ and /h/-initiated) in two jaw postures (normal and open). Number of participants: females = 38 and males = 27, n = the number of tokens (2 posture x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture
			F0	
Normal Pitch				
Females	76	F(3,34) = 2.333, p = 0.091	F(1,34) = 12.262, p = **0.001***	F(3,34) = 0.459, p = 0.713
Males	54	F(3,23) = 4.122, p = **0.018***	F(1,23) = 19.236, p < **0.001****	F(3,23) = 2.997, p = 0.052
/ma/				
Females	76	F(3,34) = 3.027, **p = 0.043***	F(1,34) = 3.517, p = 0.069	F(3,34) = 0.426, p = 0.736
Males	54	F(3,23) = 5.029, **p = 0.008***	F(1,23) = 13.330, **p = 0.001***	F(3,23) = 1.476, p = 0.247
/ha/				
Females	76	F(3,34) = 2.284, p = 0.097	F(1,34) = 4.424, **p = 0.043***	F(3,34) = 1.154, p = 0.342
Males	54	F(3,23) = 3.132, **p = 0.045****	F(1,23) = 11.030, **p = 0.003***	F(3,23) = 1.102, p = 0.369
Low Pitch				
Females	76	F(3,34) = 0.945, p = 0.430	F(1,34) = 2.213, p = 0.146	F(3,34) = 1.726, p = 0.180
Males	50[§]	F(3,21) = 3.068, p = 0.050	F(1,21) = 1.242, p = 0.278	F(3,21) = 0.481, p = 0.699
High Pitch				
Females	76	F(3,34) = 0.468, p = 0.706	F(1,34) = 6.167, **p = 0.018***	F(3,34) = 0.618, p = 0.608
Males	54	F(3,23) = 1.351, p = 0.283	F(1,23) = 8.369, **p = 0.008***	F(3,23) = 0.780, p = 0.517
			Speed Quotient	
Normal Pitch				
Females	76	F(3,34) = 0.883, p = 0.459	F(1,34) = 3.532, p = 0.069	F(3,34) = 0.589, p = 0.626
Males	54	F(3,23) = 1.382, p = 0.273	F(1,23) = 4.186, p = 0.052	F(3,23) = 2.512, p = 0.084
/ma/				
Females	76	F(3,34) = 0.697, p = 0.560	F(1,34) = 0.019, p = 0.892	F(3,34) = 0.450, p = 0.719
Males	54	F(3,23) = 0.799, p = 0.507	F(1,23) = 2.456, p = 0.131	F(3,23) = 1.000, p = 0.410
/ha/				
Females	76	F(3,34) = 0.578, p = 0.633	F(1,34) = 1.140, p = 0.293	F(3,34) = 0.138, p = 0.937
Males	54	F(3,23) = 1.272, p = 0.307	F(1,23) = 0.208, p = 0.652	F(3,23) = 1.760, p = 0.183
Low Pitch				
Females	76	F(3,34) = 0.587, p = 0.628	F(1,34) = 3.124, p = 0.086	F(3,34) = 0.363, p = 0.780
Males	50	F(3,21) = 0.383, p = 0.766	F(1,21) = 1.260, p = 0.274	F(3,21) = 0.650, p = 0.592
High Pitch				
Females	76	F(3,34) = 0.438, p = 0.727	F(1,34) = 1.101, p = 0.302	F(3,34) = 0.746, p = 0.532
Males	54	F(3,23) = 1.493, p = 0.243	F(1,23) = 0.001, p = 0.976	F(3,23) = 0.168, p = 0.917

	n	Age effect	Posture Effect	Age x Posture
		Open Quotient		
Normal Pitch				
Females	76	F(3,34) = 0.685, p = 0.567	F(1,34) = 4.358, p = **0.044***	F(3,34) = 1.274, p = 0.299
Males	54	F(3,23) = 1.327, p = 0.290	F(1,23) = 2.670, p = 0.116	F(3,23) = 1.781, p = 0.179
/ma/				
Females	76	F(3,34) = 0.766, p = 0.540	F(1,34) = 0.099, p = 0.754	F(3,34) = 0.698, p = 0.560
Males	54	F(3,23) = 0.657, p = 0.587	F(1,23) = 1.220, p = 0.281	F(3,23) = 1.267, p = 0.309
/ha/				
Females	76	F(3,34) = 0.776, p = 0.515	F(1,34) = 0.005, p = 0.947	F(3,34) = 0.947, p = 0.429
Males	54	F(3,23) = 1.711, p = 0.193	F(1,23) = 0.453, p = 0.508	F(3,23) = 2.133, p = 0.124
Low Pitch				
Females	76	F(3,34) = 0.689, p = 0.565	F(1,34) = 2.840, p = 0.101	F(3,34) = 0.515, p = 0.675
Males	50	F(3,21) = 0.458, p = 0.715	F(1,21) = 2.342, p = 0.141	F(3,21) = 1.196, p = 0.336
High Pitch				
Females	76	F(3,34) = 0.666, p = 0.579	F(1,34) = 0.842, p = 0.365	F(3,34) = 0.786, p = 0.510
Males	54	F(3,23) = 1.720, p = 0.191	F(1,23) = 0.116, p = 0.736	F(3,23) = 0.200, p = 0.895

*Significant at 0.05 level   **Significant at 0.005 level

Appendix 47. Results from two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the EGG measures (F0, SQ, and OQ) for the vowels /i, ɔ, u, a/ embedded in the sentence "We saw two cars." produced in two jaw postures (normal and open). Number of participants: females = 33 and males = 16, n = the number of tokens (2 posture x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture
			F0	
Embedded /i/				
Females	66	F(3,29) = 1.717, p = 0.185	F(1,29) = 0.788, p = 0.382	F(3,29) = 0.935, p = 0.436
Males	33	F(3,12) = 9.094, p = **0.002***	F(1,12) = 7.164, p = **0.020***	F(3,12) = 2.155, p = 0.146
Embedded / ɔ /				
Females	66	F(3,29) = 3.499, **p = 0.028***	F(1,29) = 0.510, p = 0.481	F(3,29) = 0.662, p = 0.582
Males	33	F(3,12) = 7.924, **p = 0.004***	F(1,12) = 1.312, p = 0.274	F(3,12) = 3.041, p = 0.070
Embedded /u/				
Females	66	F(3,29) = 1.041, p = 0.389	F(1,29) = 2.870, p = 0.101	F(3,29) = 0.265, p = 0.850
Males	33	F(3,12) = 5.675, **p = 0.012***	F(1,12) = 3.341, p = 0.093	F(3,12) = 2.538, p = 0.106
Embedded /a/				
Females	66	F(3,29) = 1.183, p = 0.333	F(1,29) = 8.861, **p = 0.006***	F(3,29) = 1.536, p = 0.226
Males	33	F(3,12) = 8.513, **p = 0.003***	F(1,12) = 14.103, **p = 0.003***	F(3,12) = 14.948, **p < 0.001****
	,			
			SQ	
Embedded /i/				
Females	66	F(3,29) = 0.626, p = 0.604	F(1,29) = 0.274, p = 0.605	F(3,29) = 0.750, p = 0.531
Males	33	F(3,12) = 1.832, p = 0.195	F(1,12) = 0.00111, p = 0.974	F(3,12) = 1.909, p = 0.182
Embedded / ɔ /				
Females	66	F(3,29) = 0.593, p = 0.624	F(1,29) = 0.0688, p = 0.795	F(3,29) = 0.616, p = 0.610
Males	33	F(3,12) = 0.303, p = 0.822	F(1,12) = 0.255, p = 0.623	F(3,12) = 5.620, **p = 0.012***
Embedded /u/				
Females	66	F(3,29) = 0.987, p = 0.413	F(1,29) = 2.803, p = 0.105	F(3,29) = 0.627, p = 0.603
Males	33	F(3,12) = 2.652, p = 0.096	F(1,12) = 2.831, p = 0.118	F(3,12) = 0.354, p = 0.787
Embedded /a/				
Females	66	F(3,29) = 0.336, p = 0.799	F(1,29) = 0.0248, p = 0.876	F(3,29) = 1.359, p = 0.275
Males	33	F(3,12) = 0.539, p = 0.664	F(1,12) = 0.0812, p = 0.781	F(3,12) = 0.682, p = 0.580

	n	Age effect	Posture Effect	Age x Posture
			OQ	
Embedded /i/				
Females	66	F(3,29) = 1.236, p = 0.315	F(1,29) = 0.751, p = 0.393	F(3,29) = 0.904, p = 0.451
Males	33	F(3,12) = 2.544, p = 0.105	F(1,12) = 0.002, p = 0.968	F(3,12) = 1.233, p = 0.341
Embedded / ɔ /				
Females	66	F(3,29) = 0.289, p = 0.833	F(1,29) = 0.035, p = 0.852	F(3,29) = 0.277, p = 0.842
Males	33	F(3,12) = 0.241, p = 0.866	F(1,12) = 0.136, p = 0.718	F(3,12) = 6.107, **p = 0.009***
Embedded /u/				
Females	66	F(3,29) = 1.465, p = 0.245	F(1,29) = 3.532, p = 0.070	F(3,29) = 0.650, p = 0.589
Males	33	F(3,12) = 2.079, p = 0.157	F(1,12) = 1.533, p = 0.239	F(3,12) = 0.158, p = 0.922
Embedded /a/				
Females	66	F(3,29) = 0.647, p = 0.591	F(1,29) = 0.107, p = 0.746	F(3,29) = 1.620, p = 0.206
Males	33	F(3,12) = 0.481, p = 0.702	F(1,12) = 0.110, p = 0.745	F(3,12) = 0.694, p = 0.573

*Significant at 0.05 level **Significant at 0.005 level

Appendix 48. Results from the two-way (2 jaw postures X 4 age groups) mixed model ANOVAs performed on the Aerophone measures (SPL and MFR) for the vowel /a/ sustained at normal pitch, measures of air pressure, air flow rate, and laryngeal resistance from the /pa-pa-pa-pa-pa/ production, and jaw displacement measured for the isolated vowel /a/ sustained at normal pitch. n = the number of tokens (2 postures x number of participants) submitted for analysis.

	n	Age effect	Posture Effect	Age x Posture Effect
SPL				
Females	104	$F(3, 48) = 2.272$, $p = 0.092$	$F(1, 48) = 30.453$, $p <$ **0.001****	$F(3, 48) = 0.444$, $p = 0.723$
Males	56	$F(3, 24) = 0.952$, $p = 0.431$	$F(1, 24) = 54.355$, $p <$ **0.001****	$F(3, 24) = 2.522$, $p = 0.082$
MFR				
Females	112	$F(3, 52) = 0.580$, $p = 0.631$	$F(1, 52) = 4.049$, **$p = 0.049$***	$F(3, 52) = 0.817$, $p = 0.490$
Males	58	$F(3, 25) = 0.751$, $p = 0.532$	$F(1, 25) = 18.239$, **$p < 0.001$****	$F(3, 25) = 1.042$, $p = 0.391$
Air Pressure				
Females	108	$F(3, 51) = 0.685$, $p = 0.598$	$F(1, 51) = 51.069$, **$p < 0.001$****	$F(3, 51) = 1.191$, $p = 0.323$
Males	50	$F(3, 21) = 0.813$, $p = 0.501$	$F(1, 21) = 2.614$, $p = 0.121$	$F(3, 21) = 0.165$, $p = 0.919$
Air Flow Rate from /a/				
Females	112	$F(3, 50) = 2.025$, $p = 0.122$	$F(1, 50) = 27.926$, **$p < 0.001$****	$F(3, 52) = 1.466$, $p = 0.235$
Males	58	$F(3, 25) = 0.029$, $p = 0.993$	$F(1, 25) = 0.625$, $p = 0.437$	$F(3, 25) = 0.427$, $p = 0.735$
Laryngeal Resistance				
Females	110	$F(3, 51) = 0.608$, $p = 0.613$	$F(1, 51) = 0.608$, $p = 0.439$	$F(3, 51) = 1.975$, $p = 0.129$
Males	50	$F(3, 21) = 0.078$, $p = 0.971$	$F(1, 21) = 0.024$, $p = 0.879$	$F(3, 21) = 0.246$, $p = 0.863$
Jaw Displacement				
Females	108	$F(3, 50) = 0.703$, $p = 0.555$	$F(1, 50) = 209.882$, **$p < 0.001$****	$F(3, 50) = 0.589$, $p = 0.625$
Males	54	$F(3, 23) = 1.539$, $p = 0.231$	$F(1, 21) = 39.304$, **$p < 0.001$****	$F(3, 23) = 1.184$, $p = 0.338$

*Significant at 0.05 level **Significant at 0.005 level

Appendix 49 Means and standard deviations organized by age group (35+, 60+, 70+, and 80+) and jaw postures (normal and open) for the measures of %jitter, %shimmer, SNR, F1, F2, H1-H2 amplitude difference, SPL, and MFR obtained from an isolated vowel /a/ sustained at normal pitch, VOT from the word “cars”, and air pressure from /pa-pa-pa-pa-pa/.

Figure 49.1 - Females %jitter

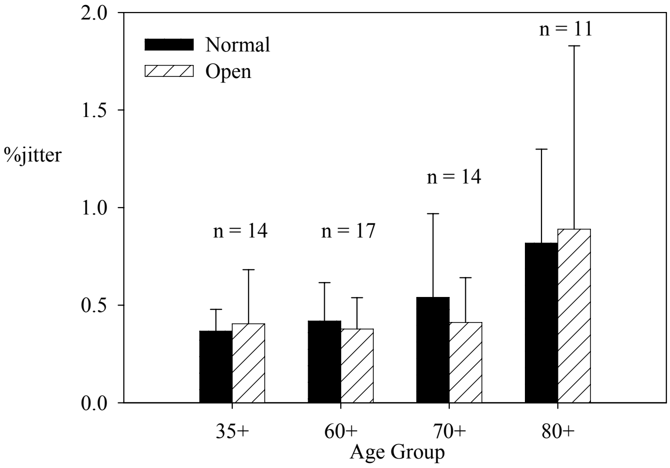


Figure 49.2 - Males %jitter

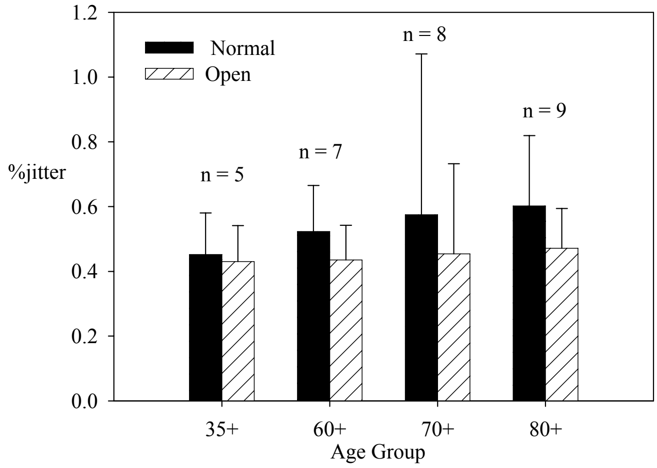


Figure 49.3 - Females %shimmer

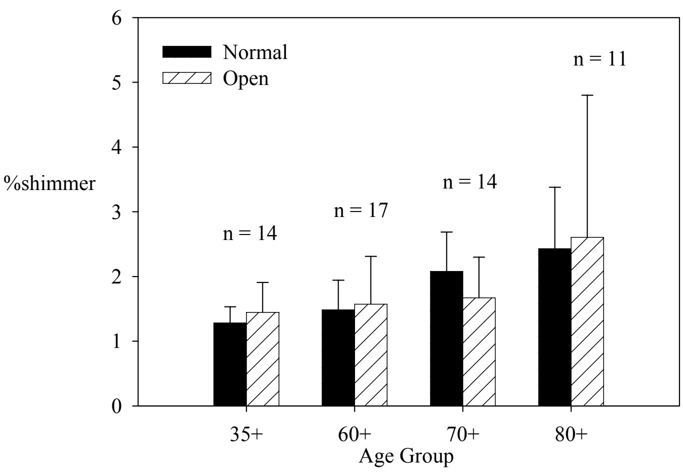


Figure 49.4 - Males %shimmer

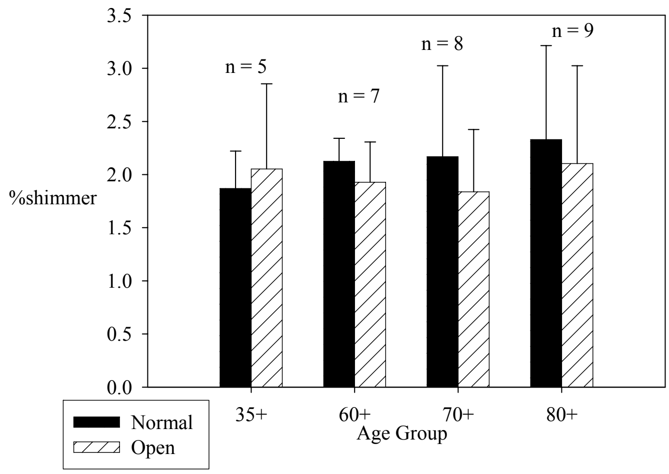


Figure 49.5 - Females SNR

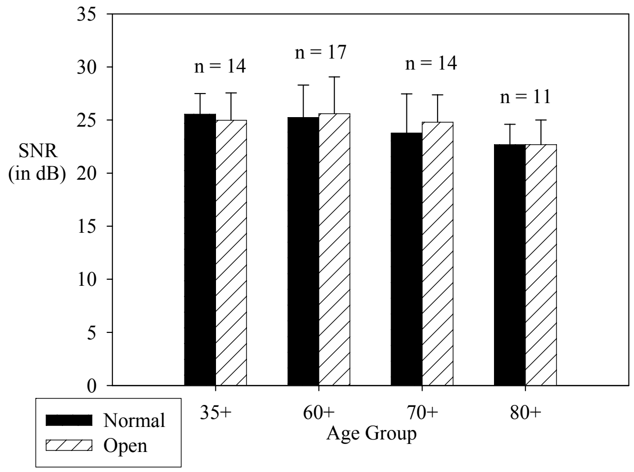


Figure 49.6 - Males SNR

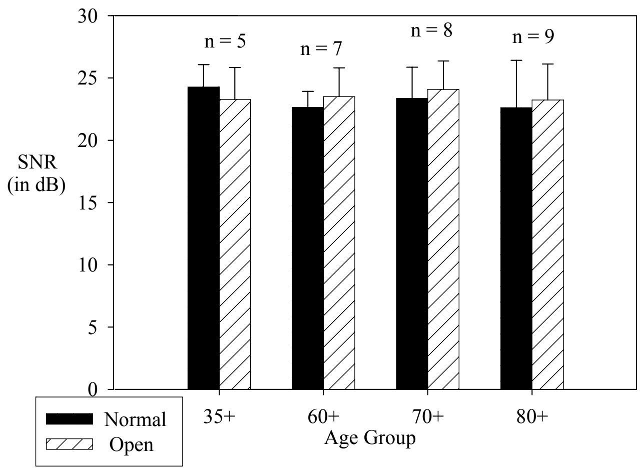


Figure 49.7 - Females F1

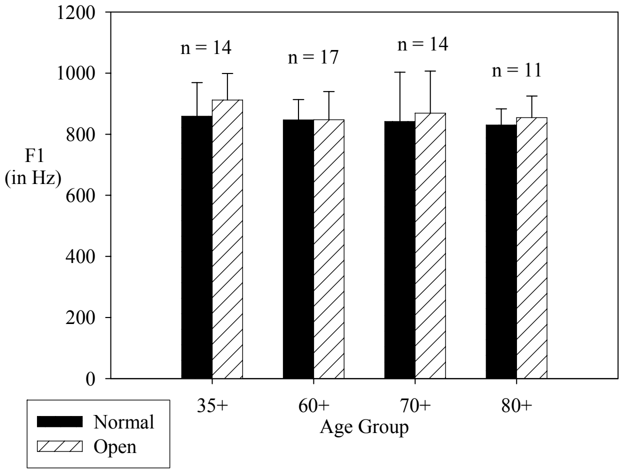


Figure 49.8 - Males F1

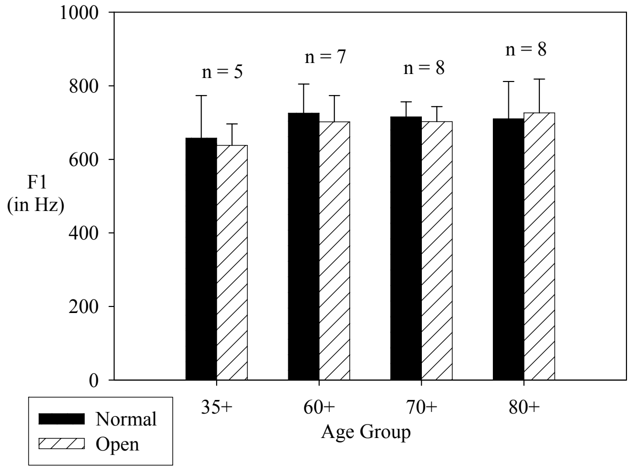


Figure 49.9 - Females F2

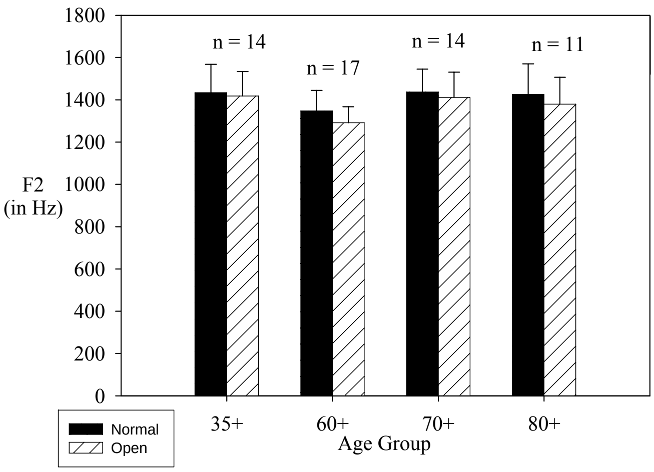


Figure 49.10 - Males F2

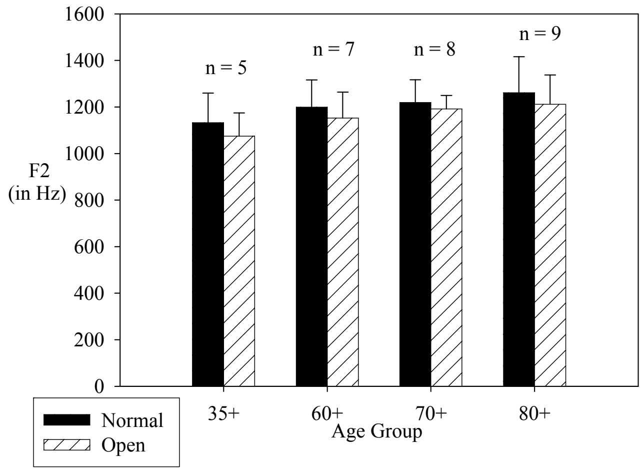


Figure 49.11 - Females H1-H2

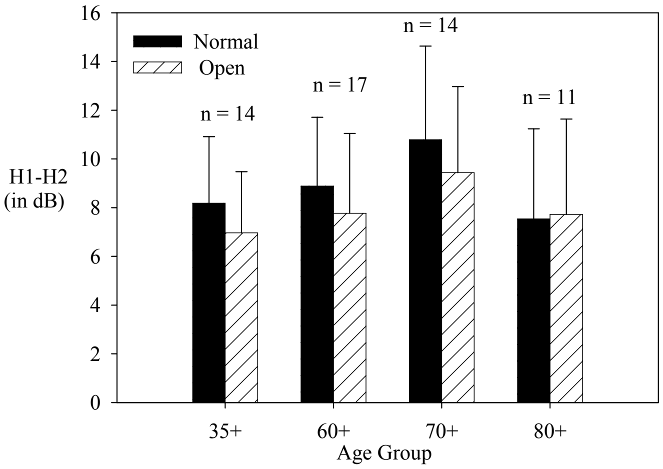


Figure 49.12 - Males H1-H2

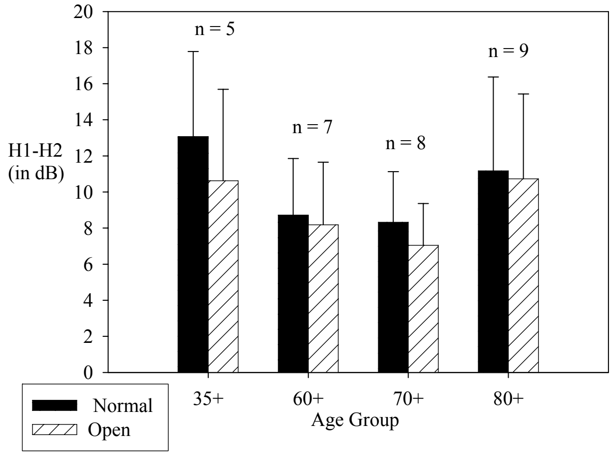


Figure 49.13 - Females VOT "cars"

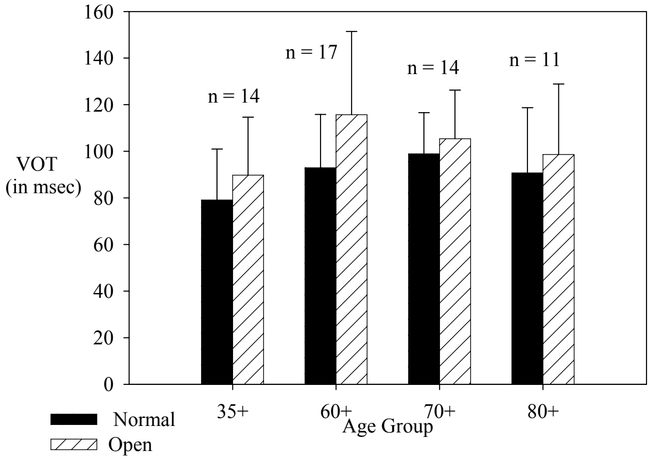


Figure 49.14 - Males VOT "cars"

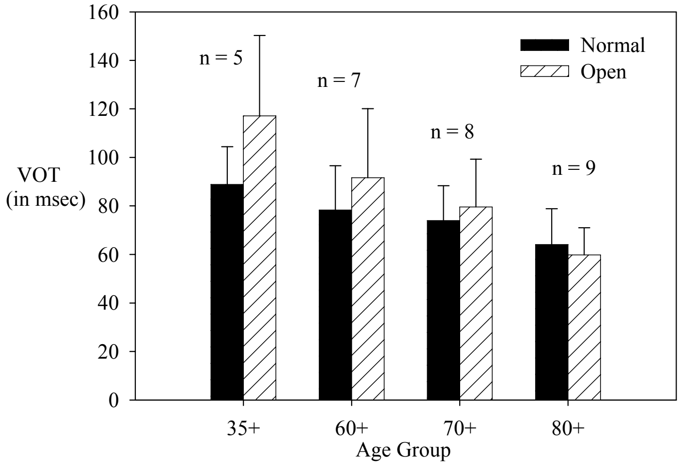


Figure 49.15 - Females SPL

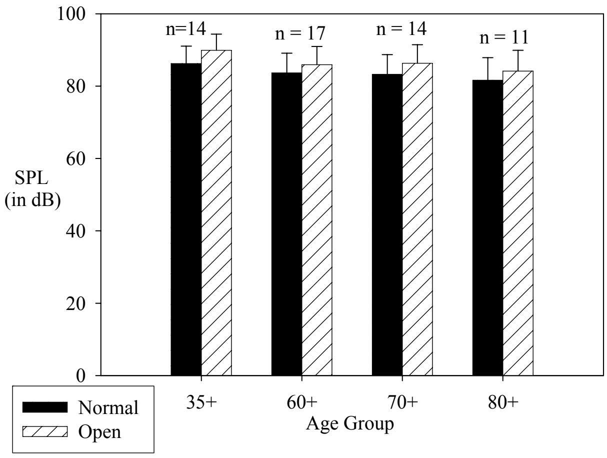


Figure 49.16 - Males SPL

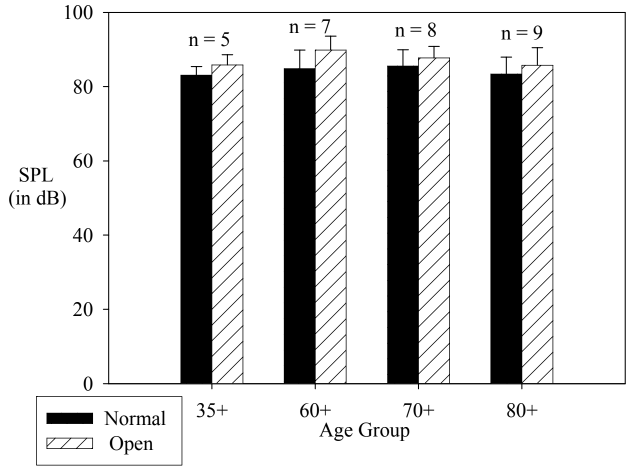


Figure 49.17 - Females MFR

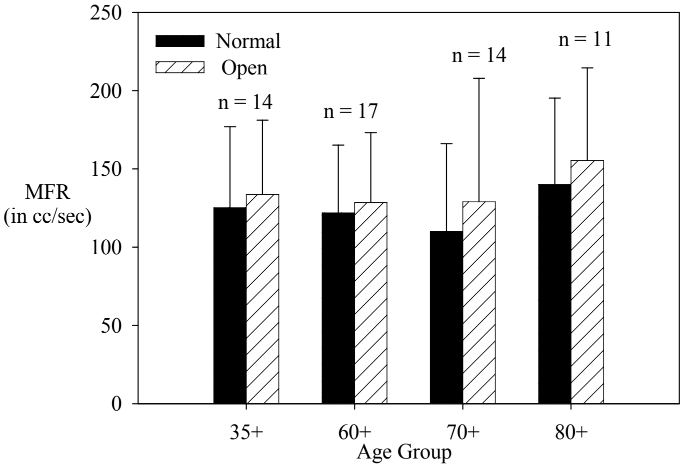


Figure 49.18 - Males MFR

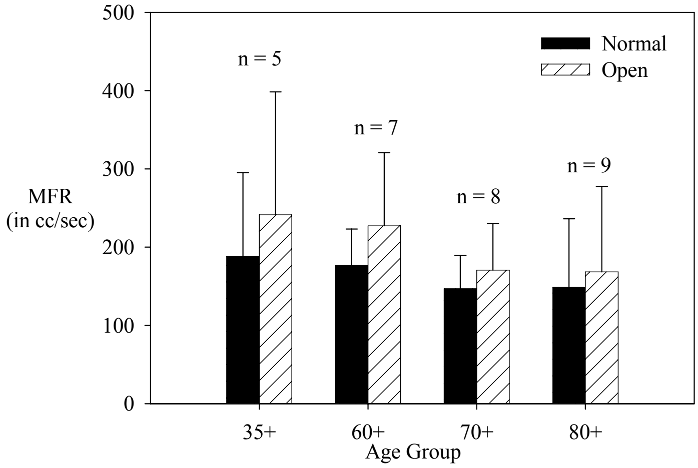


Figure 49.19 - Females Air Pressure

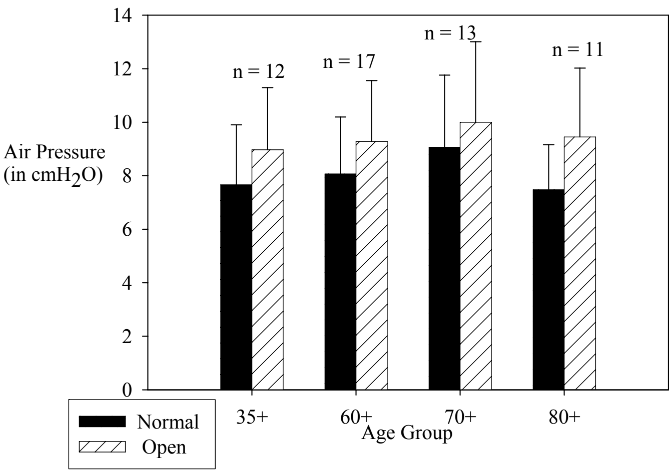
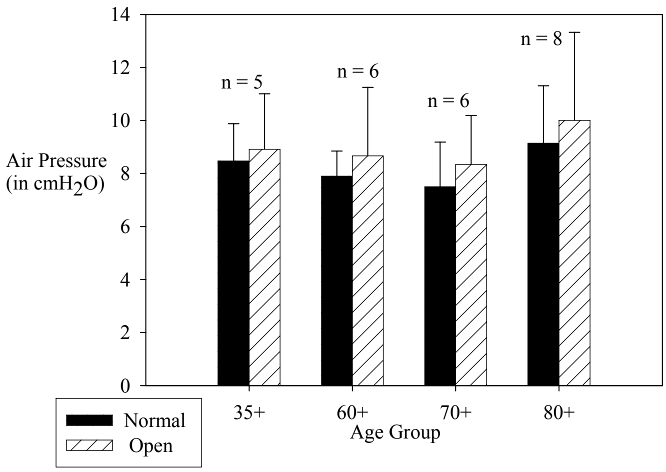


Figure 49.20 - Males Air Pressure



Appendix 50. Results from the two-way (4 age groups X 4 vowels) mixed model ANOVAs performed on the embedded vowels /i, ɔ, u, a/ from the sentence "We saw two cars" in normal and open jaw posture for females (n = 56) and males (n = 29) separately and females and males in one group. Number of participants: females = 56 and males = 29, n = the number of tokens (4 vowels x number of participants) submitted for analysis.

	n	Age effect	Vowel Effect	Age Group x Vowel Effect
			F0	
Females				
Normal	224	F(3,156) = 0.525, p = 0.667	F(3,156) = 70.665, **p < 0.001****	F(9,156) = 2.766, **p = 0.005***
Open Jaw	224	F(3,156) = 1.275, p = 0.293	F(3,156) = 95.355, **p < 0.001****	F(9,156) = 2.848, **p = 0.004***
Males				
Normal	116	F(3,75) = 3.552, **p = 0.029***	F(3,75) = 27.779, **p < 0.001****	F(9,75) = 1.607, p = 0.129
Open Jaw	116	F(3,75) = 3.841, **p = 0.022***	F(3,75) = 8.963, **p < 0.001****	F(9,75) = 1.963, p = 0.056
			%jitter	
Females				
Normal	224	F(3,156) = 1.551, p = 0.212	F(3,156) = 21.486, **p < 0.001****	F(9,156) = 0.572, p = 0.818
Open Jaw	224	F(3,156) = 0.748, p = 0.529	F(3,156) = 18.493, **p < 0.001****	F(9,156) = 0.831, p = 0.589
Males				
Normal	116	F(3,75) = 0.461, p = 0.712	F(3,75) = 9.637, **p < 0.001****	F(9,75) = 0.660, p = 0.742
Open Jaw	116	F(3,75) = 1.575, p = 0.220	F(3,75) = 14.314, **p < 0.001****	F(9,75) = 0.789, p = 0.627
			%shimmer	
Females				
Normal	224	F(3,156) = 0.796, p = 0.501	F(3,156) = 4.607, **p = 0.004***	F(9,156) = 0.944, p = 0.489
Open Jaw	224	F(3,156) = 0.638, p = 0.594	F(3,156) = 4.511, **p = 0.005***	F(9,156) = 0.951, p = 0.483
Males				
Normal	116	F(3,75) = 1.183, p = 0.336	F(3,75) = 4.386, **p = 0.007***	F(9,75) = 0.698, p = 0.708
Open Jaw	116	F(3,75) = 2.226, p = 0.110	F(3,75) = 11.935, **p < 0.001****	F(9,75) = 1.510, p = 0.160
			SNR	
Females				
Normal	224	F(3,156) = 0.588, p = 0.625	F(3,156) = 70.452, **p < 0.001****	F(9,156) = 1.516, p = 0.147
Open Jaw	224	F(3,156) = 0.467, p = 0.707	F(3,156) = 98.407, **p < 0.001****	F(9,156) = 1.942, p = 0.050
Males				
Normal	116	F(3,75) = 2.226, p = 0.110	F(3,75) = 11.935, **p < 0.001****	F(9,75) = 1.510, p = 0.160
Open Jaw	116	F(3,75) = 1.702, p = 0.192	F(3,75) = 66.071, **p < 0.001****	F(9,75) = 1.699, p = 0.104
			F1	
Females				
Normal	224	F(3,156) = 2.541, p = 0.066	F(3,156) = 471.704, **p< 0.001****	F(9,156) = 0.619, p = 0.780
Open Jaw	224	F(3,156) = 1.886, p = 0.143	F(3,156) = 465.041, **p < 0.001****	F(9,156) = 0.933, p = 0.498
Males				
Normal	116	F(3,75) = 0.492, p = 0.691	F(3,75) = 239.376, **p < 0.001****	F(9,75) = 1.898, p = 0.065
Open Jaw	116	F(3,75) = 0.778, p = 0.517	F(3,75) = 239.844, **p < 0.001****	F(9,75) = 1.602, p = 0.130
			F2	
Females				
Normal	224	F(3,156) = 0.553, p = 0.649	F(3,156) = 708.749, **p < 0.001****	F(9,156) = 1.364, p = 0.209
Open Jaw	224	F(3,156) = 0.672, p = 0.573	F(3,156) = 719.665, **p < 0.001****	F(9,156) = 1.374, p = 0.204
Males				
Normal	116	F(3,75) = 0.246, p = 0.863	F(3,75) = 299.912, **p < 0.001****	F(9,75) = 1.072, p = 0.393
Open Jaw	116	F(3,75) = 0.826, p = 0.492	F(3,75) = 190.870, **p < 0.001****	F(9,75) = 1.457, p = 0.180

*Significant at 0.05 level **Significant at 0.005 level